VARIABLE-RATIO VERSUS VARIABLE-INTERVAL SCHEDULES: RESPONSE RATE, RESISTANCE TO CHANGE, AND PREFERENCE

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Two experiments asked whether resistance to change depended on variable-ratio as opposed to variable-interval contingencies of reinforcement and the different response rates they establish. In Experiment 1, pigeons were trained on multiple random-ratio random-interval schedules with equated reinforcer rates. Baseline response rates were disrupted by intercomponent food, extinction, and prefeeding. Resistance to change relative to baseline was greater in the interval component, and the difference was correlated with the extent to which baseline response rates were higher in the ratio component. In Experiment 2, pigeons were trained on multiple variable-ratio variable-interval schedules in one half of each session and on concurrent chains in the other half, in which the terminal links corresponded to the multiple-schedule components. The schedules were varied over six conditions, including two with equated reinforcer rates. In concurrent chains, preference strongly overmatched the ratio of obtained reinforcer rates. In multiple schedules, relative resistance to response-independent food during intercomponent intervals, extinction, and intercomponent food plus extinction depended on the ratio of obtained reinforcer rates but was less sensitive than was preference. When reinforcer rates were similar, both preference and relative resistance were greater for the variable-interval schedule, and the differences were correlated with the extent to which baseline response rates were higher on the variable-ratio schedule, confirming the results of Experiment 1. These results demonstrate that resistance to change and preference depend in part on response rate as well as obtained reinforcer rate, and challenge the independence of resistance to change and preference with respect to response rate proposed by behavioral momentum theory.

Key words: variable-ratio schedules, variable-interval schedules, resistance to change, response rate, preference, key peck, pigeons

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In multiple schedules, response rate is more resistant to change in the component with the higher reinforcer rate or amount, and this difference is at least ordinally equivalent across a variety of disrupters (for reviews, see Nevin, 1979, 1992b). A number of studies have found that resistance to change was independent of baseline response rate established by the response–reinforcer contingency and depended instead on rate of reinforcement signaled by a distinctive stimulus—that is, the Pavlovian stimulus–re-

inforcer contingency (e.g., Nevin, Tota, Torquato, & Shull, 1990; for review, see Nevin & Grace, 2000a). Thus, if reinforcer variables are equated, performances maintained by different schedule contingencies in two multiple-schedule components should be equally resistant to change, regardless of the response rates established by those contingencies.

Branch (2000) suggested that a comparison of variable-ratio (VR) and yoked variable-interval (VI) schedules would provide an interesting test of this expectation. It is well established that ratio schedules maintain higher response rates than interval schedules over a wide range of reinforcer rates. For example, Baum (1993) arranged VR schedules in one component of a multiple schedule, with yoked VI schedules in the second component, and varied reinforcer rates from about 20 per hour to over 1,000 per hour. Response rates were consistently higher in the VR component at all reinforcer rates below 1,000 per hour. Zuriff (1970) had previ-

ously reported similar results for responding on multiple VR VI schedules that did not involve yoking, as had Herrnstein (1964) for responding on VR versus VI schedules in the terminal links of concurrent chains. Thus, if reinforcer rates are equated between VR and VI schedules, any differences in resistance to change could be attributed to differences in ratio versus interval contingencies and the response rates they establish.

To our knowledge, the only directly relevant data on resistance to change with interval and ratio contingencies are those of Lattal, Reilly, and Kohn (1998). They arranged alternating exposure to progressive-ratio schedules and to interval schedules yoked to the progressive-ratio schedules, and found that responding generally persisted in the yoked-interval schedules well beyond the point at which responding on the progressive-ratio schedules had stopped. However, there were no consistent differences in average response rates between the two conditions in their study, so the authors suggested that some properties of ratio versus interval contingencies, rather than the response rates they maintained, were responsible for the difference in persistence.

Several other experiments have examined resistance to change in relation to explicit interresponse-time (IRT) contingencies that control baseline response rates in multiple schedules with the same reinforcer rate in each component. With pigeons as subjects, Fath, Fields, Malott, and Grossett (1983) failed to find differential resistance to intercomponent food in responding maintained at different rates by tandem pacing contingencies in multiple VI VI schedules, consistent with the independence of resistance and response rate. By contrast, in a similar experiment with rats as subjects, Blackman (1968) found that high response rates were relatively less resistant to conditioned suppression than were low response rates. Lattal (1989) compared tandem VI fixed-ratio (FR) and tandem VI differential-reinforcement-of-low-rate (DRL) schedules with pigeons, and found that the high rates maintained by the tandem FR were less resistant to intercomponent food than were the low rates maintained by the tandem DRL. Blackman's and Lattal's results suggest that low response rates are more resistant to change than high rates, and chal-

lenge the sufficiency of Pavlovian determination of resistance to change. However, pacing or tandem schedules that explicitly reinforce IRTs may establish different response units in the schedule components, such as response bursts on tandem FR or pause-then-respond on DRL. Differences in resistance to change of average response rate might reflect complex effects on the components of such units. For example, if pausing on DRL is disrupted, average response rate might increase, whereas if responding is disrupted, average response rate should decrease. Thus, the data on resistance to change in relation to response rates controlled by explicit IRT contingencies are hard to interpret.

VR and VI schedules also differ in their molar feedback functions and IRT contingencies, and similar interpretive difficulties may arise. Unlike DRL and pacing contingencies or tandem FR requirements, however, both VR and VI schedules arrange immediate reinforcement for a simple response unit (e.g., a single key peck) after varying times and numbers of responses since a previous reinforcer. Moreover, the IRT contingencies in VR and VI schedules are weaker in that a response may be reinforced after any IRT. Therefore, any differences in resistance to change between VR and VI schedules would more strongly challenge the generality of Pavlovian contingencies as the sole determiners of resistance to change (for review, see Nevin & Grace, 2000a).

To compare the effects of ratio and interval contingencies on resistance to change, Experiment 1 arranged multiple random-ratio (RR) random-interval (RI) schedules. We used RR and RI rather than VR and VI schedules in order to equate reinforcer rates over successive components by on-line computer control, adjusting the probability of reinforcement per second in the RI component at the end of every RR component. After baseline performances were stable, resistance to change was examined during disruption by response-independent food during intercomponent intervals, extinction, and prefeeding.

EXPERIMENT 1
Method
Subjects

Four homing pigeons with extensive experience on multiple schedules with yoked RR

and RI components were maintained at 80% to 85% of their ad lib weights by postsession feedings as needed. Water and grit were continuously available in their home cages.

Apparatus

Four similar chambers, approximately 40 cm by 40 cm by 35 cm, were equipped with three keys 21 cm above the floor, a houselight situated 8 cm above the center key, and a grain feeder situated 13 cm below the center key. Only the center key, which could be lighted red or green, was used. A force of 0.10 N was required to operate the key. Reinforcement was 2.5-s access to the lighted grain feeder, with houselight and key darkened. Chambers were ventilated by fans, which also provided masking noise. The experiment was controlled and data were recorded by a computer running Med-PC® software, situated in an adjacent room.

Procedure

Daily sessions consisted of 48 components (30 s each) separated by 20-s blackouts; blackouts were introduced progressively over the first seven sessions. Red and green components alternated regularly. When the key was lighted red, food reinforcers were scheduled according to an RR 60 schedule, which was arranged by interrogating a probability gate after every response. The probability value was 1/60 in the RR component throughout the experiment. When the key was green, food reinforcers were scheduled according to an RI schedule, arranged by interrogating a probability gate every second. The probability value in the RI component depended on observed response rate in the RR component in the previous and current sessions. Specifically, the expected rate of reinforcement for the RR component in the previous session (observed responses per minute divided by 60) was converted to a probability of reinforcement per second at the start of a session. At the start of each presentation of the RI component, the probability value was updated by averaging it with the expected rate of reinforcement (based on observed response rate) in the most recent presentation of the RR component. Because sessions always began with an RR component, the probability used in the first presentation of the RI component was based on the RR performance averaged

Table 1

Number of sessions of baseline training and testing in Experiment 1.

Procedure	Sessions
Baseline	30+
RT .03 (108/hr)	7 (12 for C2)
Baseline	28
RT .06 (216/hr)	6
Baseline	61
RT .12 (432/hr)	5
Baseline	10
Extinction	12
Baseline	30
Prefeeding	5

over the previous session combined with that in the first RR component of the current session. Sessions always started with a 20-s blackout and were conducted at about the same time, 7 days per week.

After all subjects had at least 30 sessions of baseline training, response rates appeared to be stable in both components, and a series of resistance tests was conducted. The first type of test, designated RT, presented food during intercomponent blackouts at random times. Three successive tests arranged that food was presented with probabilities of .03, .06, or .12 per second, resulting in about 108, 216, and 432 food presentations per hour of blackout. After the three RT tests and baseline recovery, food reinforcement was discontinued altogether in both components (extinction). After a final baseline recovery, subjects received 30 g of food in their home cages 1 hr before their sessions for 5 consecutive days (designated PF). A minimum of 10 sessions of baseline training intervened between tests. Table 1 gives the number of sessions of baseline training and testing.

RESULTS

Numerical data are summarized in Table 2, which shows that baseline response rates, averaged over 10 sessions before each resistance test, were consistently greater in the RR component than in the RI component and were reasonably well replicated after each resistance test. However, response rates in the RI component tended to increase over the course of the experiment for all birds. On average, response rates in the RR component were more than double the response rates in the RI component. Obtained reinforcer rates

Table 2

Responses per minute and obtained reinforcers per hour, averaged for the final 10 sessions of baseline before each resistance test, and responses per minute averaged for the first five sessions of each resistance test.

Bird		Response rates		Reinforcer rates		Test type	Resistance	
		RR	RI	RR	RI		RR	RI
C1	BL	112.2	20.6	119.6	106.0	RT .03	103.4	36.5
	BL	101.9	24.7	126.3	119.5	RT .06	108.3	39.4
	BL	123.6	16.2	125.2	107.7	RT .12	102.5	44.6
	BL	122.4	21.9	143.6	114.8	Ext	119.4	41.6
	BL	111.4	39.9	147.0	128.1	PF	83.5	43.0
	M	114.3	24.7	132.3	115.2			
C2	BL	113.4	32.4	95.6	88.7	RT .03	101.3	35.8
	BL	115.8	38.2	84.2	89.7	RT .06	108.9	42.7
	BL	109.9	36.1	96.2	94.7	RT .12	96.9	43.3
	BL	107.3	44.6	87.6	90.5	Ext	86.8	36.9
	BL	100.3	45.2	84.8	80.7	PF	36.9	13.0
	M	109.3	39.3	89.7	88.9			
C3	BL	100.4	42.2	101.8	98.8	RT .03	107.7	46.9
	BL	106.7	48.8	97.3	80.8	RT .06	102.5	52.2
	BL	109.5	50.1	93.9	78.2	RT .12	77.5	26.4
	BL	110.5	57.0	94.8	89.9	Ext	91.4	54.4
	BL	109.2	46.8	106.6	85.1	PF	111.0	68.8
	M	107.3	49.0	98.9	86.6			
C4	BL	114.6	54.3	88.6	78.6	RT .03	105.7	74.3
	BL	110.7	57.4	110.3	102.7	RT .06	66.8	34.4
	BL	109.9	62.9	111.0	98.9	RT .12	104.7	64.2
	BL	103.5	62.9	110.8	110.2	Ext	104.5	78.6
	BL	114.7	79.7	93.0	83.8	PF	89.0	41.8
	M	110.7	63.4	102.7	94.8			

were slightly greater in the RR component for all but Bird C3, but the proportion of reinforcers obtained in the RR component never exceeded .56. Accordingly, the procedure satisfies the conditions necessary for evaluation of resistance to change in ratio and interval components with differing response rates and similar reinforcer rates.

Figure 1 summarizes the session-by-session data for resistance to change, expressed as log proportion of baseline in the preceding 10 sessions. Contrary to the results of some previous studies (e.g., Nevin, Mandell, & Atak, 1983), response rates did not decrease reliably during RT tests as a function of the rate of intercomponent food. Instead, response rates increased relative to baseline in several cases, most often in the RI component and substantially so for Bird C1. Also contrary to some previous results, response rates sometimes exceeded baseline during prefeeding, especially for Bird C3.

To evaluate possible differences in the structure of RR and RI responding, we examined relative frequency distributions of IRTs before and during the third RT test. Figure 2 shows the percentage of IRTs in class intervals of 10 ms for the last five sessions of baseline and the five sessions of the test. Percentages were calculated for each session, then averaged over sessions, and finally smoothed using the moving average calculat-

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Fig. 1.   Multiple-schedule response rates in Experiment 1 during resistance test sessions, expressed as log proportions of baseline response rates in the immediately preceding 10 sessions. The connected sets of data points represent, from the left, the first five sessions of RT .03, RT .06, and RT .12; the first 12 sessions of extinction; and all five sessions of PF. The left point in each connected set represents baseline (0). Data for RI components are given by diamonds connected by dashed lines, and data for RR components are given by squares connected by solid lines. Data points were omitted when response rates were zero.
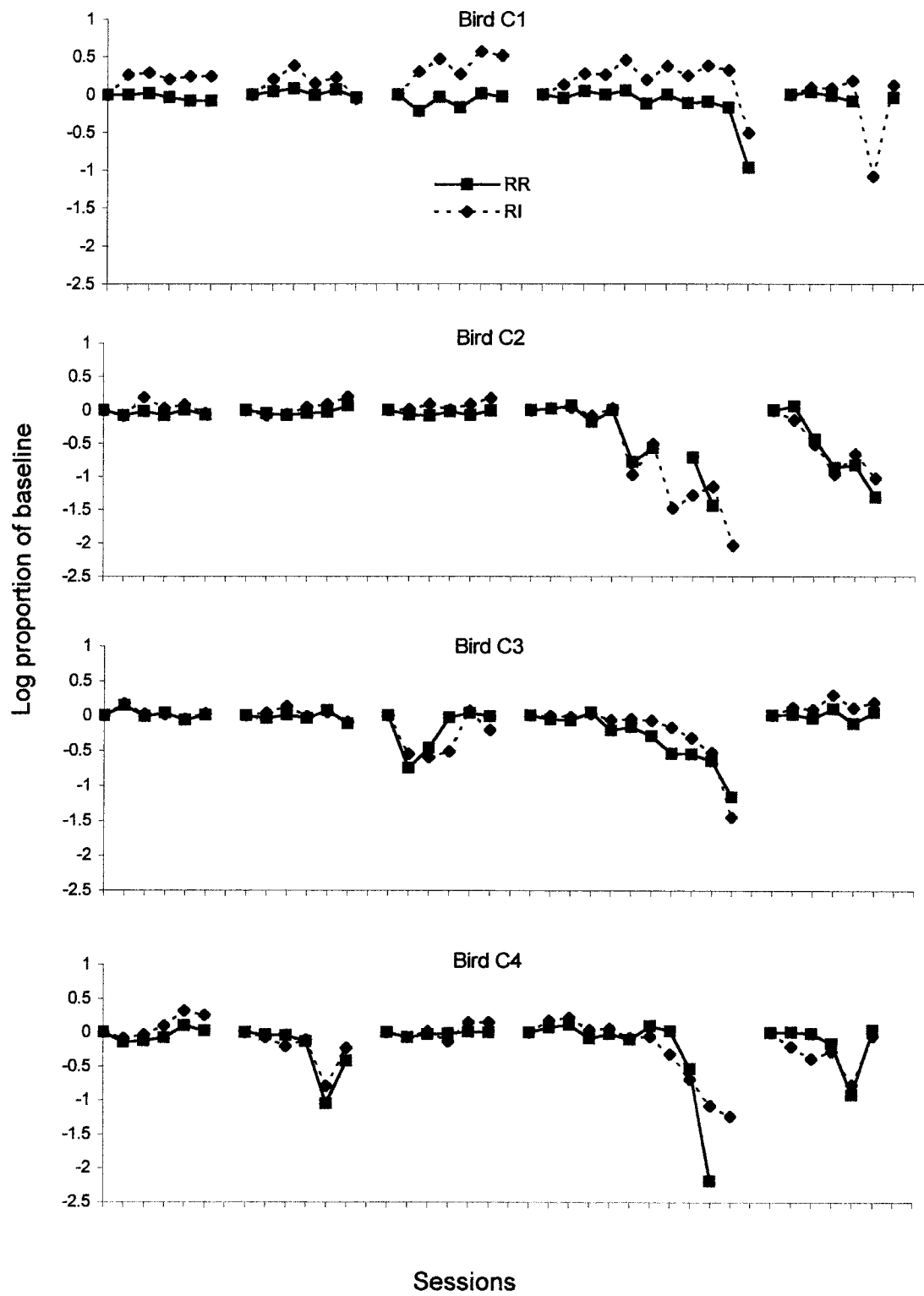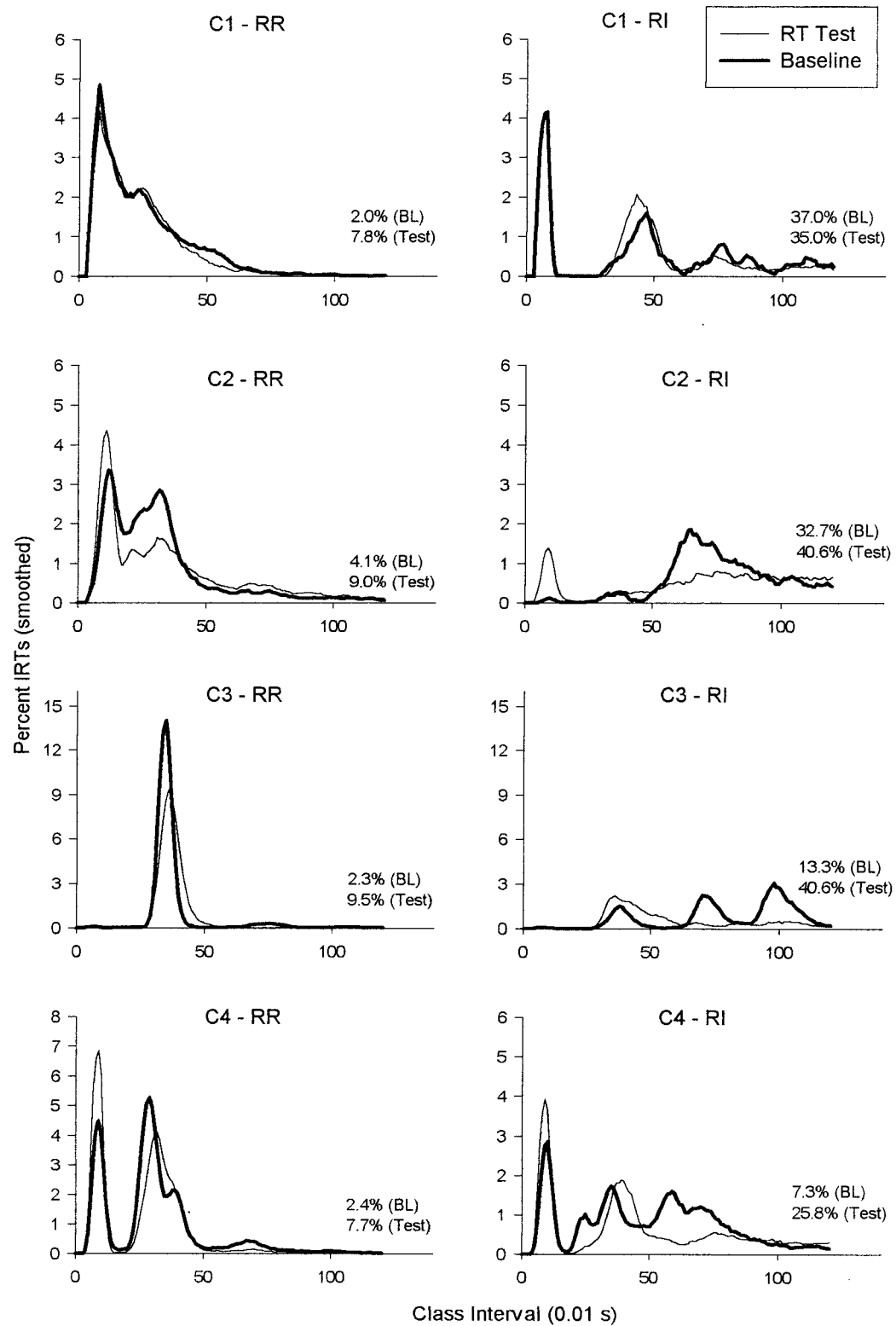
ed over five class intervals. The class-interval analysis was limited to IRTs less than 1.2 s because there was no obvious structure in longer IRTs.

A well-defined mode in an IRT distribution suggests a frequently occurring behavioral sequence or unit of more or less constant duration that occurs between pecks. Performances on different schedules may involve mixtures of units with different durations. Baseline IRT distributions suggest different response units in the RR and RI components, in that RR distributions were heavily concentrated in one or two modes below 0.5 s, whereas multiple modes at longer IRTs characterized most RI distributions. In the RT test, the locations of these modes remained essentially constant in the RR component, with small and idiosyncratic shifts in the RI components. A number of distributions show increases in the heights of earlier relative to later modes. The rough constancy in the locations of the modes suggests that the differing behavioral units established by RR and RI schedules were not disrupted during the test, but instead ocurred more or less frequently in conjunction with changes in average response rates. Accordingly, all further analyses are based on average response rates.

Average response rates for the first five sessions of each resistance test are presented in Table 2. To quantify the effects of the various disrupters, these averages (designated B_x) were expressed as the logarithms of the proportions of the averages for the immediately preceding baselines (designated B_o). Relative resistance to change—the difference in disruptive effects between RI and RR components—was expressed as log (B_{xRI}/B_{oRI}) − log (B_{xRR}/B_{oRR}), where the terms are subscripted to indicate the RI or RR component. This difference measure of relative resistance, which has been used throughout our recent work (e.g., Nevin & Grace, 2000b), was positive in 17 of 20 cases, signifying that response rate was usually higher relative to baseline in the RI component than in the RR component during resistance tests. Moreover, the differ-

ence was correlated with the log ratio of baseline response rates, log (B_{oRR}/B_{oRI}). Figure 3 presents individual data for relative resistance to RT, to extinction, and to PF in relation to the log ratio of baseline response rates during the 10 baseline sessions immediately preceding each test. Pooled across subjects and resistance tests, the correlation was significantly positive ($r = .83$, $p < .01$). Note that the reinforcement yoking procedure, which was in effect throughout all resistance tests (except extinction), precludes confounding by differences in obtained reinforcement. We conclude that when the reinforcer rate for an RR schedule is similar to that for an RI schedule, relative resistance is greater in the interval schedule to the extent that the ratio schedule maintains a higher response rate during baseline.

DISCUSSION

The role of schedule contingencies and response rates in the determination of resistance to change contradicts the general conclusion of a number of previous studies, all of which used VI schedules, that resistance to change is independent of baseline response rate. This independence is fundamental to the metaphor of behavioral momentum, where baseline response rate is analogous to the velocity of a moving body and resistance to change is analogous to the mass of that body. These data also challenge many previous findings that behavioral mass depends on stimulus–reinforcer contingencies and not on response–reinforcer contingencies (for review, see Nevin & Grace, 2000a). However, some of the present resistance data were anomalous, in that disrupters that have usually decreased response rates in our previous research led instead to rate increases in several cases, and because of these increases, our conclusions depend on the use of the difference measure of relative resistance to change. For example, if we had calculated the ratio of log (B_{xRI}/B_{oRI}) to log (B_{xRR}/B_{oRR}), we would have obtained large negative ratios rather than positive differences for cases in which RI

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Fig. 2.   Smoothed relative frequency distributions of IRTs in the RR and RI components during the last five sessions of baseline preceding the third RT test (heavy lines) and during all five sessions of the RT test (light lines). The percentage of IRTs longer than 1.2 s is shown in each panel. See text for explanation of the smoothing method.
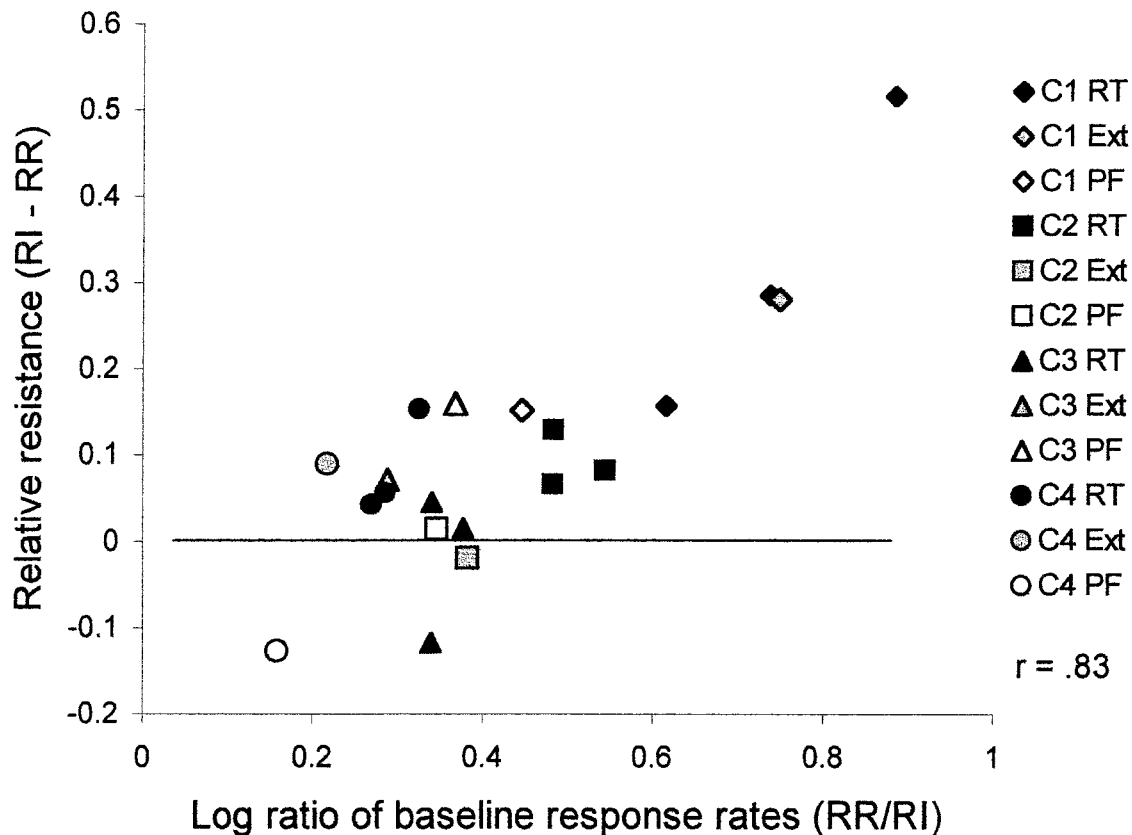
Fig. 3. The correlation between relative resistance (the log proportion of baseline in the RI component minus the log proportion of baseline in the RR component) and log multiple-schedule baseline response-rate ratios (RR/ RI) in Experiment 1. Data points are coded for type of resistance test; data for the three RT resistance tests are plotted separately. The horizontal line at 0 signifies no difference in resistance to change between RI and RR components.

response rate increased and RR response rate decreased slightly during a test.

Previous research has sometimes found response-rate increases in one or both components of multiple VI VI schedules, most frequently in the richer component when intercomponent food was presented (e.g., Grace & Nevin, 1997). Response-rate increases in a schedule component that explicitly reinforced low response rates were also observed by Lattal (1989). We used the difference measure of relative resistance here and in previous work because it yields agreement for both increases and decreases relative to baseline, and because Nevin and Grace (2000b) showed that it is additive with respect to different disrupters as well as being sensitive to differences in reinforcer rate. To confirm the validity of our measure and to eval-

uate the reliability of the findings of Experiment 1, we conducted a parametric study comparing resistance to change and preference for ratio versus interval schedules, using the procedure of Nevin and Grace (2000b).

EXPERIMENT 2

Experiment 2 examined both resistance to change and preference with VR and VI (rather than RR and RI) schedules in multiple-schedule components and in the terminal links of concurrent chains. Preference in concurrent chains is relevant to comparisons of VR and VI performances because differences in resistance to change are generally correlated with preference (see Nevin & Grace, 2000a, for review). Grace and Nevin (1997)

developed a paradigm that measures both aspects of behavior within subjects and experimental conditions. In this paradigm, one half of each session arranges a two-component multiple schedule on a center key, in which the components are separated by intercomponent intervals. The other half arranges concurrent-chains schedules, in which initial-link responding on two side keys gives access to one or the other of two terminal links on the center key. The terminal links are identical to the multiple-schedule components, and the duration of the initial links approximates the intercomponent interval in the multiple-schedule phase. Resistance to change is measured in the multiple-schedule phase, and preference between the terminal links is measured in the concurrent-chains phase.

Grace and Nevin (1997) found that when the VI schedules in terminal links and multiple-schedule components were varied across conditions, both preference and relative resistance (measured as in Experiment 1) covaried with the ratio of reinforcer rates. The covariation of preference in concurrent chains and resistance to change in multiple schedules has substantial generality (e.g., Grace, Bedell, & Nevin, in press; Grace & Nevin, 2000; Grace, Schwendiman, & Nevin, 1998; Nevin & Grace, 2000b). Thus, if resistance to change is affected by ratio versus interval contingencies and the resulting differences in response rate, as suggested by Experiment 1, then preference should be affected similarly.

Contrary to this expectation, Herrnstein (1964) reported that preference between VR and VI schedules was independent of schedule type, and depended only on relative terminal-link reinforcer rates. However, Herrnstein arranged variable-duration terminal links that ended after two reinforcers were obtained. Grace and Nevin (2000; see also Nevin & Grace, 2000b) found that both relative resistance and preference were more sensitive to the ratio of reinforcer rates with VI schedules in constant-duration components of the sort used in Experiment 1 than in the variable-duration components used by Grace and Nevin (1997). Accordingly, the first four conditions of Experiment 2 arranged VR and VI schedules in constant-duration multiple-schedule components and

terminal links, with different reinforcer rates between components or terminal links depending on the schedule values and the subjects' response rates. In two subsequent conditions, reinforcer rates were kept approximately equal by adjusting the value of the VR schedule over blocks of sessions. After stable baseline response rates were established, responding was disrupted by presenting response-independent food during intervals between multiple-schedule components (VT), by discontinuing response-contingent food in the schedule components (extinction), and by a combination of intercomponent food and extinction in the schedule components (VT+ext). The central question is whether resistance to change and preference are affected by ratio versus interval schedules, and if so, whether the baseline response rates established by the different schedule contingencies are critical for the results, as suggested by Experiment 1.

METHOD

Subjects

Four White Carneau pigeons with histories of reinforcement on multiple schedules served as subjects. Initially, the birds were maintained at 85% of their free-feeding body weights, but even with no postsession feeding, they tended to gain weight over the course of the experiment on the basis of reinforcers obtained per session. Because there were no discernible effects on response rate, no attempt was made to restrict access to food during the session. The birds were housed individually in a vivarium with a 12:12 hr light/dark cycle, with lights on at 7:00 a.m.

Apparatus

The experiment was conducted in four similar three-key pigeon chambers, 35 cm deep by 35 cm wide by 35 cm high. The keys were 26 cm above the floor, 2.6 cm in diameter, and separated by 8 cm, center to center. An aperture (6 cm by 5 cm) 13 cm below the center key gave access to a grain feeder, and a houselight was located 7 cm above the center key. Reinforcement consisted of 2-s access to the feeder. The keys could be transilluminated with red, green, or white light, and were operated by pecks with a force of about 0.10 N. Blowers provided ventilation and

masking noise. The experiment was controlled and data were recorded by a computer running MED-PC® software, located in an adjacent room.

Procedure

Baseline. Sessions consisted of a multiple-schedule procedure in one half and a concurrent-chains procedure in the other half, in random order from day to day. Session halves were separated by a 3-min blackout. Sessions were conducted daily at about the same time of day (3:00 p.m.) with few exceptions.

Concurrent-chains procedure. For consistency with our previous research using this general method, we begin by describing the concurrent-chains half of each session. There were 24 initial- and terminal-link cycles of concurrent chains in each session, and each cycle began with the center key dark and the two side keys lighted white to define the initial links. A terminal-link entry was assigned randomly to either the left or right key, with the restriction that exactly 12 entries to each terminal link were assigned during the session half. An initial-link response was reinforced by terminal-link entry provided that (a) it was to the preselected key, (b) an interval selected from an arithmetic VI 15-s schedule had elapsed, and (c) a 1.5-s changeover delay was satisfied. The VI schedule contained 12 intervals that were sampled randomly, with the restriction that each interval preceded a left or a right terminal-link entry exactly once per session half. The initial-link VI schedule did not begin timing until the first peck to either side key in each cycle.

Terminal-link entry was signaled by lighting the center key red or green and extinguishing the side keylights. For Birds 291 and 303, the red-key schedule followed left-key pecks and the green-key schedule followed right-key pecks; one terminal link was a VR schedule and the other was a VI schedule. For Birds 292 and 320, these color assignments were reversed. The VI schedules were constructed from Fleshler–Hoffman (1962) progressions containing 18 intervals. The VR schedules were based on Fleshler–Hoffman progressions rounded to the nearest integer, with the highest value adjusted to make the average equal to the nominal scheduled value. Values for both VI and VR schedules were sampled without replacement. Terminal links

were always 30 s long (excluding reinforcement), after which the next cycle began at once.

In Conditions 1 and 2, the schedules were VI 18 s and VR 18, with assignments to red and green reversed between conditions. Because the VR schedules maintained high response rates, the obtained reinforcer rate for VR was greater than for VI. In Conditions 3 and 4, the VI schedule values were calculated for each bird to yield the same average reinforcer rate as had been obtained in the VR component of the multiple schedule in Conditions 1 and 2, and the VR schedule values were calculated to yield the same average reinforcer rate as had been obtained on the VI schedules. The latter calculation assumed that VR response rate in Conditions 3 and 4 would be the same as the average VR response rate in the multiple-schedule components in Conditions 1 and 2. As a result, the obtained reinforcer rate for VI was greater than for VR in Conditions 3 and 4. In Conditions 5 and 6, the VR and VI schedule values were calculated for each bird to yield the same overall average reinforcer rate as in Condition 4. Initially, the value of the VR was chosen to yield the same reinforcer rate as that arranged by the VI schedule, assuming that the VR response rate would be the same as in the multiple VR component of Condition 4. The VR value was then adjusted up or down every 5 to 10 sessions so as to maintain rough equality between obtained reinforcer rates. For example, if the average obtained reinforcer rates in a five-session block were 5% greater in the VR component, the average VR schedule value was lengthened by 5% for the next block of sessions. For Birds 291 and 292 in Condition 5, the VR schedule was assigned to the component color that had signaled the VI schedule in Condition 4. For Birds 303 and 320, color assignments for VR and VI schedules in Condition 5 were the same as in Condition 4. Key-color assignments were reversed for all birds in Condition 6. The VR and VI schedule values in each condition are listed in Table 3.

Multiple-schedule procedure. In the multiple-schedule session half, there were 24 components signaled by lighting the center key red or green in random order, with the restriction that exactly 12 of each occurred during each session. Key colors signaled VR or VI

Table 3

Schedules in the terminal links produced by responding on the left and right keys during initial links of the concurrent chains and in the corresponding multiple-schedule components, and number of sessions preceding the first resistance test in each condition of Experiment 2. VR schedules designated t were adjusted every five to ten sessions to equate obtained VR and VI reinforcer rates. The order of resistance tests was VT, VT + ext, and ext in Conditions 1, 3, 5, and 6, and VT + ext, VT, and ext in Conditions 2 and 4. VI times are in seconds.

	Bird 291		Bird 292		Bird 303		Bird 320		
Condition	Left	Right	Left	Right	Left	Right	Left	Right	Sessions
1	VI 18	VR 18	VI 18	VR 18	VI 18	VR 18	VI 18	VR 18	50
2	VR 18	VI 18	VR 18	VI 18	VR 18	VI 18	VR 18	VI 18	60
3	VR 37	VI 7.5	VR 42	VI 7.35	VR 51	VI 5.86	VR 44	VI 6.92	31
4	VI 7.5	VR 37	VI 7.35	VR 42	VI 5.86	VR 51	VI 6.92	VR 44	49
5	VR 25t	VI 10.4	VR 24t	VI 10.9	VI 9.5	VR 24t	VI 10.5	VR 24t	80
6	VI 10.4	VR 25t	VI 10.9	VR 24t	VR 24t	VI 9.5	VR 24t	VI 10.5	32

schedules programmed exactly as in the terminal links of the concurrent chains, and components were always 30 s long (excluding reinforcement). For convenience, components corresponding to the terminal links produced by the left- or right-key initial link will be designated "left" and "right." Components were separated by a 30-s intercomponent interval (ICI) to approximate the average time spent in the initial links in the concurrent chains.

Resistance tests. Three different tests of resistance to change were conducted in each condition, separated by a series of baseline sessions. The concurrent-chains half of the session was omitted during these tests.

1. Intercomponent VT food (VT). Food was presented during the ICI between multiple-schedule components according to a VT 10-s schedule for five consecutive sessions while baseline VR and VI schedules remained in effect. The duration of food presentation was 2 s.

2. Intercomponent VT food plus extinction (VT+ext). Food was presented exactly as in the VT food test, and no reinforcers were delivered in the VR and VI schedule components for five consecutive sessions.

3. Extinction. The VR and VI schedules were discontinued for seven or eight consecutive sessions.

Sequence and duration of conditions. In each condition, baseline training continued until performance appeared to be stable for all 4 birds by visual inspection of the data. Then, either a VT or a VT+ext test was conducted, in an irregular order across conditions. The other test was conducted after at least eight sessions of baseline training intervened. Finally, an extinction test was conducted after at least eight more baseline sessions intervened. The full sequence of conditions and tests is summarized in Table 3.

RESULTS

Again for consistency with our previous research using this general method, we begin by describing initial-link preference, followed by baseline terminal-link and multiple-schedule response rates, resistance to change, and the correlations among these measures. All calculations are based on the individual data in the Appendix.

Preference

The upper panel of Figure 4 presents the mean log initial-link response ratios for all subjects for the last 10 sessions of each condition before the first resistance test. For each subject, preference followed the changes in reinforcer rate in the terminal links produced by responding on the left and right keys over the first four conditions, and approximated indifference in Conditions 5 and 6 in which reinforcer rates were kept approximately equal. The lower panel shows the regression slopes for log initial-link response ratios over those 10 sessions in each condition. The regression slopes fall between ±0.05 and do not deviate systematically from zero, which indicates that any trends within these data were small relative to the strong control exerted by the terminal-link schedules. Thus, choice responding was generally stable before
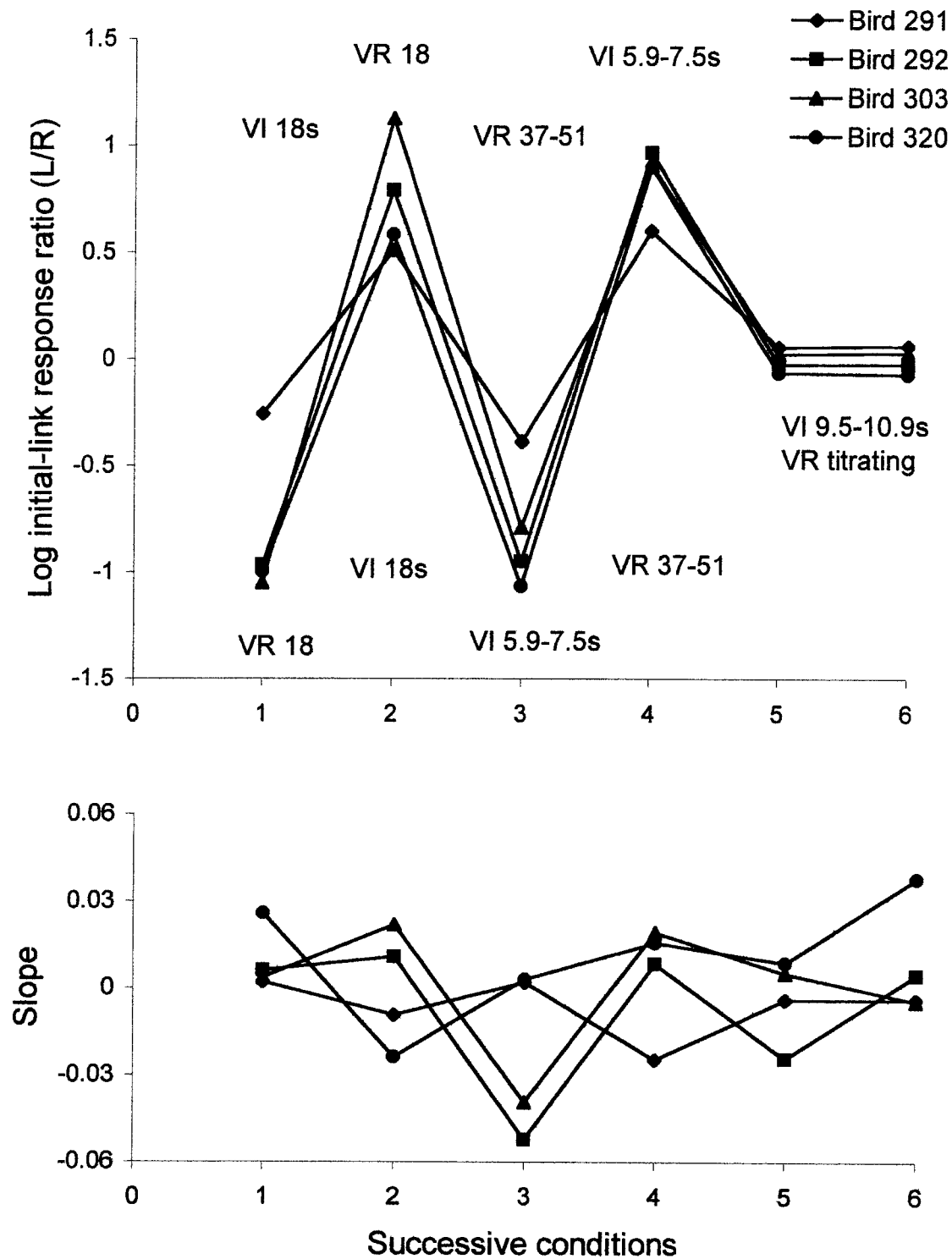
Fig. 4. The upper panel shows initial-link preference during the final 10 sessions of baseline before the first resistance test in each condition, with the left and right terminal-link schedules indicated above and below the data for Conditions 1 through 4. In Conditions 5 and 6, reinforcer rates were kept about equal by titrating the value of the VR schedule, with left and right terminal-link assignments counterbalanced. The lower panel shows the slopes of regression lines characterizing trends in preference over those 10-session blocks.

the first resistance test in each condition, and we used the mean of the last five baseline sessions to characterize asymptotic performance.

The relations between log initial-link response ratios in the last five sessions of baseline before each resistance test and log obtained terminal-link reinforcer ratios for those sessions are presented by the filled diamonds and squares in Figures 5, 6, and 7. Figure 5 presents the preference data before the VT test, which alternated irregularly with VT+ext as the first or second test within conditions; Figure 6 presents the data before the VT+ext test; and Figure 7 presents the data before the extinction test, which was always third. (The open symbols show relative resistance to change, which will be discussed below.) Overall, the data are well described by a logarithmic version of the generalized matching law, which is implied by Grace's (1994) contextual choice model when average programmed initial- and terminal-link durations are constant across conditions:

$$\log (B_{iL}/B_{iR}) = a_p \log (r_{tL}/r_{tR}) + \log b_p. \ (1)$$

In this equation, B_{iL} and B_{iR} are initial-link responses on the left and right keys, and r_{tL} and r_{tR} are obtained reinforcer rates in the terminal links produced by left and right initial links, respectively. The parameter a represents the sensitivity of the initial-link response ratio to the terminal-link reinforcer ratio, and log b represents bias toward the left or right key; both are subscripted p to designate preference. Parameter values estimated by least squares regression are given in Table 4, together with variance accounted for. Across subjects and tests, the value of a_p ranged from 1.47 to 2.97, with a mean of 2.22, indicating strong overmatching. An average of 90% (range, 80% to 97%) of the data variance was explained by Equation 1. These results demonstrate strong and reliable overmatching.

Strong overmatching was also reported by Nevin and Grace (2000b) with VI VI schedules in constant-duration terminal links in a procedure similar to that employed here. Nevin and Grace reported sensitivity values ranging from 1.39 to 2.10, with a mean of 1.79. Although the ranges overlap, the average value of sensitivity in the present experiment is greater than that found by Nevin and

Grace. The greater overall sensitivity to terminal-link reinforcer rates in the present experiment may be due to the use of 15-s initial links. Averaged across conditions, the obtained initial-link durations were 21.7 s, 29.2 s, 24.9 s, and 27.8 s for Birds 291, 292, 303, and 320, respectively, all of which were shorter than the terminal-link duration of 30 s. By contrast, Nevin and Grace used 25-s initial links, and the obtained initial-link durations were always longer than their 30-s terminal links. Thus, our results are consistent with findings that preference sensitivity is inversely related to initial-link length (e.g., Fantino, 1969; cf. Grace, 1994).

Preference for VI Versus VR Terminal Links

Close inspection of Figures 5, 6, and 7 suggests that when the VI terminal link was produced by the left initial link, the data points often lie above the fitted lines. When the VI terminal link was produced by the right initial link, the data points often lie below the lines. To the extent that these deviations are reliably different in direction, they provide evidence of preference for the VI terminal link that is independent of the obtained reinforcer ratio. Table 4 presents the difference between the average deviations from the fitted lines between conditions in which the VI schedule was produced by the left or right initial link, showing that the overall difference was positive for all 4 subjects. Pooled across baseline determinations and conditions, these differences were reliably different from zero for Birds 291 (two-tailed t test, $p < .001$) and 292 ($p < .05$), and for all differences pooled across subjects ($p < .001$). This is evidence of preference for VI over VR schedules when variations in reinforcer rates were taken into account by fits to Equation 1.

We also examined preference for VI over VR schedules separately in Conditions 5 and 6, in which reinforcer rates were roughly equated for VI and VR terminal links produced by left-key or right-key initial-link responses, reversed between conditions and counterbalanced across birds. Rather than comparing preference with fitted estimates, we used actual obtained reinforcer rates in the terminal links for blocks of five sessions preceding each resistance test. Initial-link responses to the left and right keys and rein-
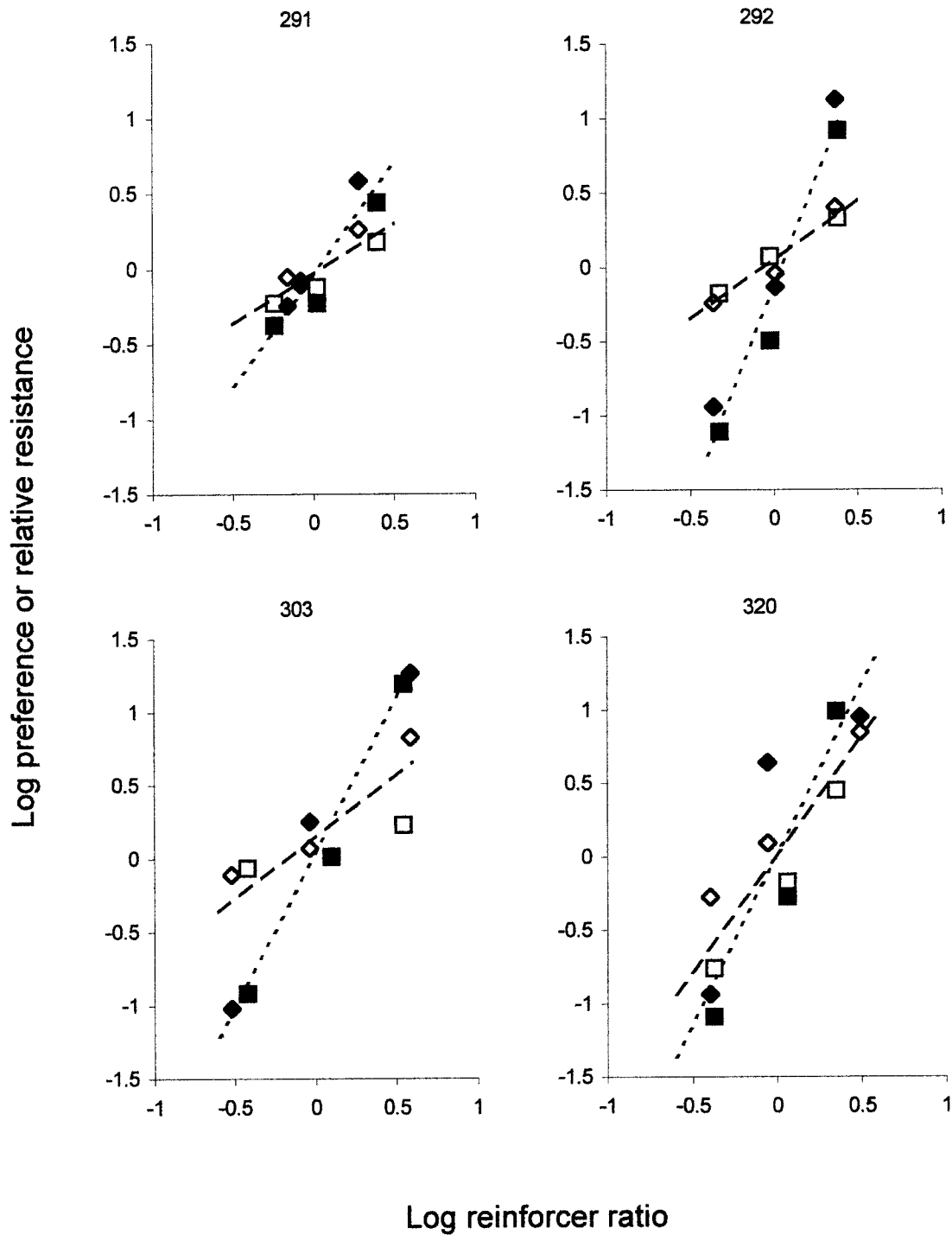
Fig. 5. Initial-link preference during five-session blocks before VT tests expressed as the log ratio of left-key to right-key responses (filled symbols), and relative resistance to VT (open symbols) in multiple-schedule components corresponding to left and right terminal links in concurrent chains, as functions of log obtained reinforcer ratios in those terminal links and components. Dotted lines represent fits of Equation 1 for preference, and dashed lines represent fits of Equation 3 for relative resistance. Diamonds indicate conditions in which the VI terminal link and its corresponding multiple-schedule component were produced by the left-key initial link, and squares indicate conditions in which the VI terminal link and its corresponding multiple-schedule component were produced by the right-key initial link.
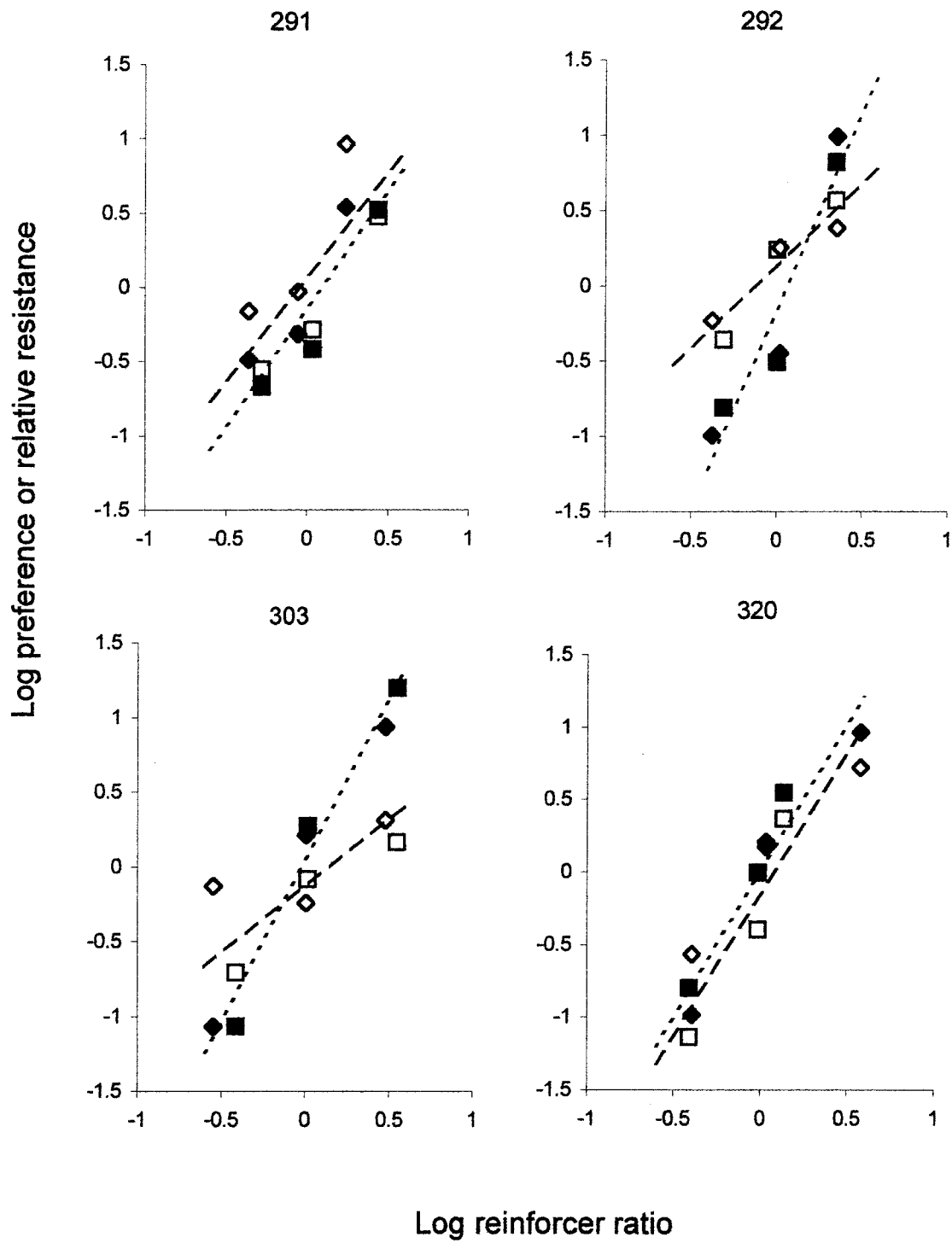
Fig. 6. Initial-link preference during five-session blocks before VT+ext tests and relative resistance to VT+ext, presented as in Figure 5.
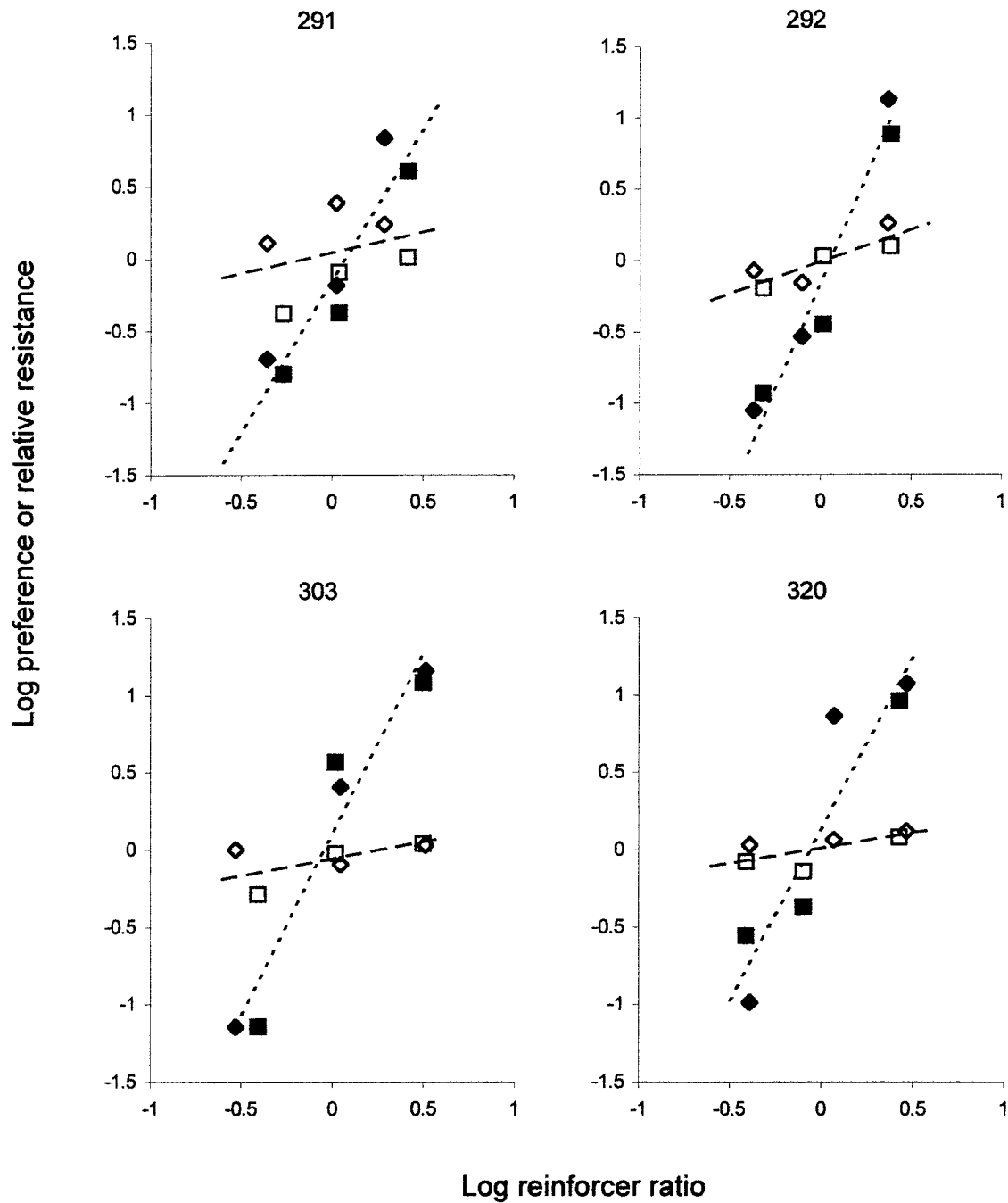
Fig. 7. Initial-link preference during five-session blocks before extinction tests and relative resistance to extinction, presented as in Figures 5 and 6.

forcers in the terminal links produced by those responses, averaged over Conditions 5 and 6 to eliminate key-position and color biases, are presented in Figure 8. If our method for equating baseline reinforcer rates had worked perfectly, all data points would be stacked over a log reinforcer ratio of zero. Although log obtained reinforcer ratios var-

Table 4

Parameters a_p and log (b_p) of Equation 1 for preference in baseline sessions preceding each type of resistance test, and parameters a_m and $\log(b_m)$ of Equation 3 for relative resistance. Also shown are the differences in the average deviations, in log units, from prediction by Equations 1 and 3 when VI schedules were arranged in the terminal links produced by the left or right initial link and in the corresponding multiple-schedule components. Positive differences indicate that VI schedules were preferred or were more resistant to change when reinforcer rates were taken into account by Equations 1 or 3.

Bird	Test	Preference				Resistance			
		a_p	$\log(b_p)$	VAC	Deviation	a_m	$\log(b_m)$	VAC	Deviation
291	VT	1.47	−0.04	.86	+0.199*	0.67	−0.03	.81	+0.132*
	VT + ext	1.57	−0.15	.81	+0.296	1.39	0.06	.58	+0.552*
	ext	2.08	−0.16	.86	+0.343*	0.29	0.04	.11	+0.425*
292	VT	2.85	−0.13	.96	+0.274*	0.80	0.05	.95	−0.026
	VT + ext	2.61	−0.18	.91	+0.057	1.10	0.13	.90	+0.005
	ext	2.97	−0.16	.95	+0.188	0.45	−0.01	.74	+0.061
303	VT	2.08	0.04	.97	+0.209	0.85	0.15	.63	+0.228
	VT + ext	2.13	0.04	.97	+0.045	0.90	−0.13	.63	+0.214
	ext	2.32	0.10	.93	+0.040	0.22	−0.06	.34	+0.066
320	VT	2.30	0.01	.80	+0.341	1.59	0.01	.82	+0.427*
	VT + ext	2.00	0.00	.94	−0.185	1.94	−0.16	.79	+0.550*
	ext	2.20	0.13	.87	+0.144	0.20	0.01	.40	+0.115*

* $p < .05.$

ied from about −0.09 to 0.14, the average was 0.01, so our method of equating reinforcer rates was at least reasonably successful. Preference also varied within and between subjects, but the log initial-link response ratio generally favored the VI terminal link to a greater extent than expected if log obtained reinforcer ratios were the only systematic determiner of preference. The difference was substantial for Bird 320, and the only exceptions were two data points for Bird 303. Thus, when reinforcer rates were approximately equal and variations in obtained reinforcement were taken into account, VI schedules were generally preferred over VR schedules.

Baseline Response Rates

The individual data summarized in the Appendix show that VR response rates were almost always greater than VI response rates both in the terminal links of concurrent chains and in the multiple-schedule components before each resistance test, and were reasonably well recovered after each test. The differences in VR and VI response rates are illustrated in Figure 9, which shows that there were no consistent trends across conditions. Although VI response rates were somewhat greater than we have observed in related procedures (e.g., Nevin & Grace, 2000b), espe-

cially for Bird 303, the consistently higher VR response rates replicate standard findings and satisfy an important condition for the rationale of this study.

The experiment was designed so that the sum of obtained reinforcer rates for VR and VI performances was approximately constant across all conditions, whereas the reinforcer-rate ratio varied between conditions. The relation between response rate ratios and obtained reinforcer rate ratios was analyzed through a logarithmic form of the generalized matching law:

$$\log (B_{VR}/B_{VI}) = a \log (r_{VR}/r_{VI}) + \log b, \quad (2)$$

where B_{VR} and B_{VI} represent response rates in the VR and VI terminal links or multiple-schedule components, respectively, and r_{VR} and r_{VI} represent the corresponding obtained reinforcer rates. The parameter a represents the sensitivity of the response-rate ratio to the reinforcer ratio, and log b represents bias toward one schedule type when reinforcer rates are taken into account. Figure 10 shows rather irregular relations between the log ratio of response rates and the log ratio of obtained reinforcer rates for individual subjects. The lack of regularity in the individual data precludes reliable parameter estimation, but for the average data, a is 0.09
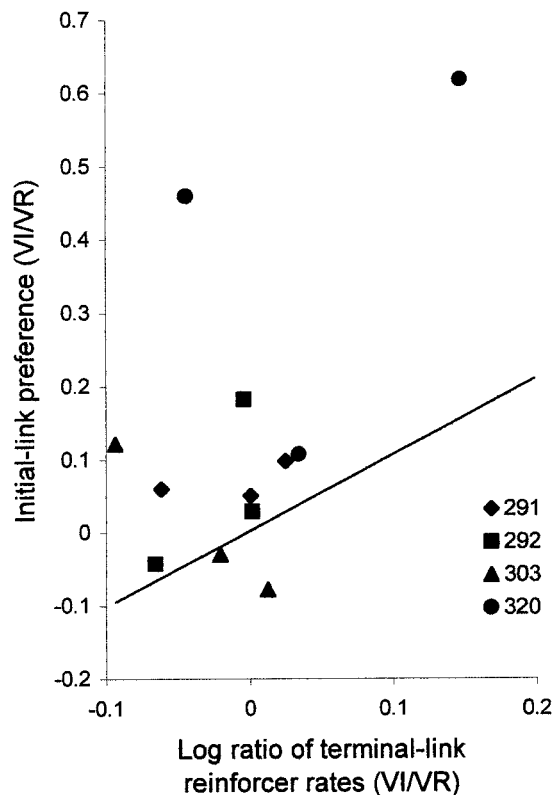
Fig. 8. The log ratio of initial-link responses that produced VI terminal links to initial-link responses that produced VR terminal links in concurrent chains, pooled for Conditions 5 and 6, plotted against the log ratio of obtained terminal-link reinforcer ratios (VI/VR). The diagonal line indicates equality of these variables. Data points falling above the line indicate that preference for the VI terminal link was greater than expected on the basis of the reinforcer ratio.

for terminal links and 0.12 for multiple schedules, indicating substantial undermatching. Log b is 0.14 for terminal links and 0.09 for multiple schedules, reflecting response-rate bias toward the VR schedules. Averaging log b over terminal links and multiple schedules and exponentiating shows that VR response rates were about 30% greater than VI response rates when variations in reinforcer rates were taken into account. This is substantially less than in Experiment 1, in which RR response rates were about 100% greater than RI response rates.

Our data are similar to those reported by Zuriff (1970) for multiple VR VI schedules, in that VR rates were consistently greater than VI rates and their ratio depended on the ratio

of obtained reinforcer rates. However, a re-analysis of Zuriff's data (see his Figure 2) showed that when reinforcer rates were equal, the VR rates were 70% greater on average than the VI rates. Because Baum (1993) found that the difference between VR and VI rates decreased as reinforcer rate increased, the greater differentiation of VR and VI rates in Zuriff's data probably arises from his use of leaner schedules. (The same factor is probably responsible for greater rate differentiation in Experiment 1.) Also, a reanalysis of Zuriff's data by McSweeney, Farmer, Dougan, and Whipple (1986) yielded generalized-matching-law slopes that averaged 0.57. Zuriff did not arrange timeout periods between components, which are known to reduce sensitivity to reinforcer rates (e.g., Nevin, 1992a; Nevin et al., 1983). Using a procedure similar to that employed here, Nevin and Grace (2000b) also found lower sensitivity to reinforcer-rate ratios in VI VI terminal links and multiple-schedule components than is typical in the multiple-schedule literature. Overall, our results accord reasonably well with the results of previous research.

Resistance to Change

Figure 11 shows how response rates, expressed as log proportions of the immediately preceding five sessions of baseline, changed during the resistance tests. Because the VR and VI schedules were the same for each pair of conditions and the colors signaling each schedule were reversed within the pair, we have averaged across reversals to remove color bias. Figure 11 shows that for most birds and conditions, the VT test produced moderate reductions in responding, but occasionally it resulted in small increases relative to baseline. The VT+ext and extinction tests had substantially greater decremental effects.

In Conditions 1 and 2, the obtained reinforcer rate was greater in the VR component, and responding was slightly more resistant to change in the VR component for most birds, although there was little difference in extinction. In Conditions 3 and 4, the obtained reinforcer rate was greater in the VI component, and responding was more resistant to change in that component for all birds in all tests. In Conditions 5 and 6, in which reinforcer rates were similar, resistance to change was similar in both components. However, in
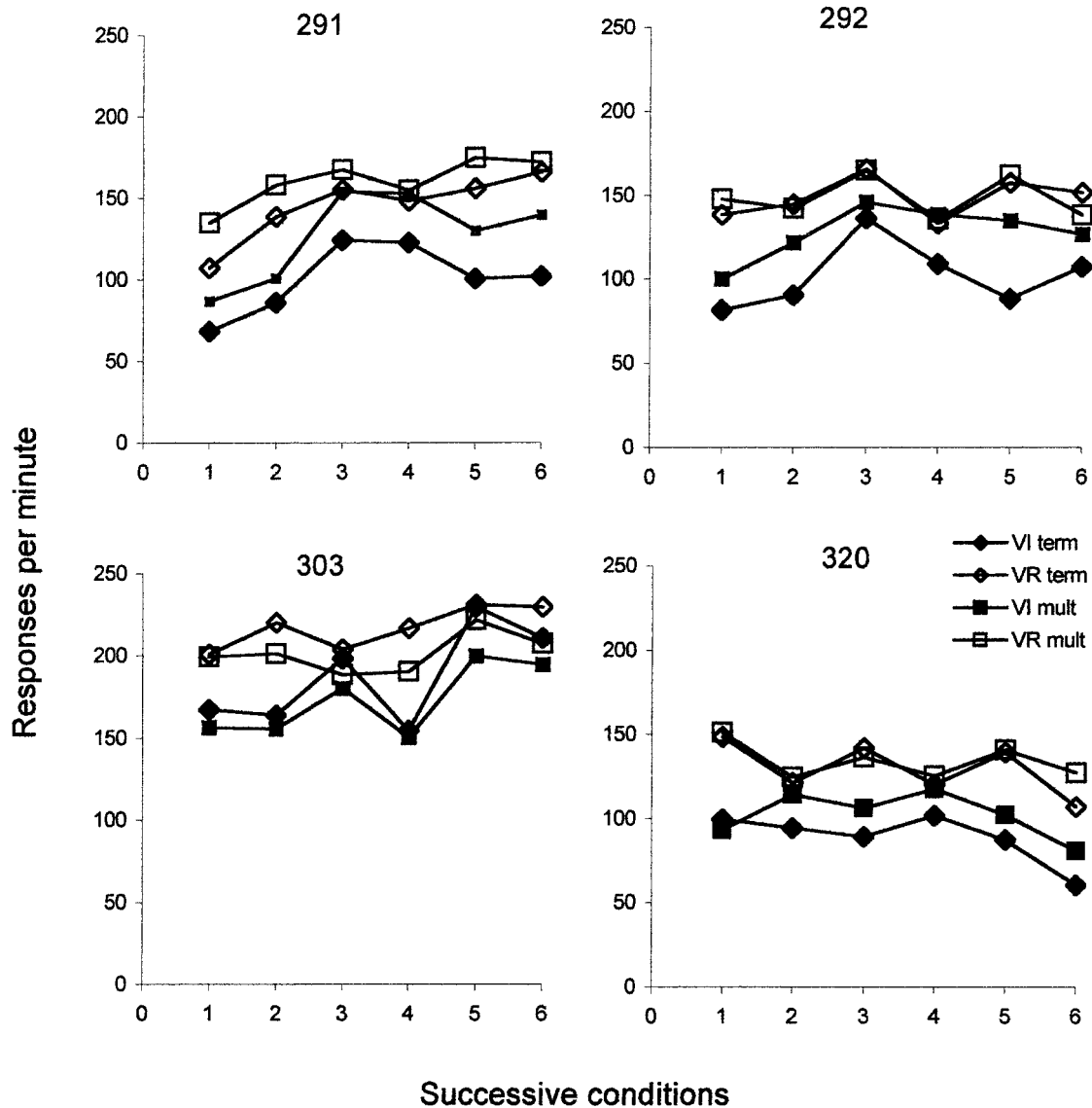
Fig. 9. Baseline response rates in VI and VR terminal links (term) and the corresponding VI and VR multiple-schedule components (mult) before the first resistance test across all six conditions of Experiment 1 for individual subjects.

those few cases for which a difference was evident, resistance was greater in the VI component (e.g., Bird 291, extinction; and Bird 320, VT+ext).

As in Experiment 1, response rates were averaged for the last five sessions of baseline preceding each resistance test, designated B_o, and for the first five sessions of each resistance test, designated B_x. Within each component, resistance to change was expressed as $\log (B_x/B_o)$, and relative resistance to change

between components was expressed as the difference between $\log (B_x/B_o)$ for the left and right components. This difference measure of relative resistance was used in Experiment 1 and in our earlier work with this paradigm (e.g., Nevin & Grace, 2000b). The relation between relative resistance and the ratio of reinforcer rates is given by

$$\log (B_{xL}/B_{oL}) - \log (B_{xR}/B_{oR})$$

$$= a_m \log (r_R/r_L) + \log b_m, \qquad (3)$$
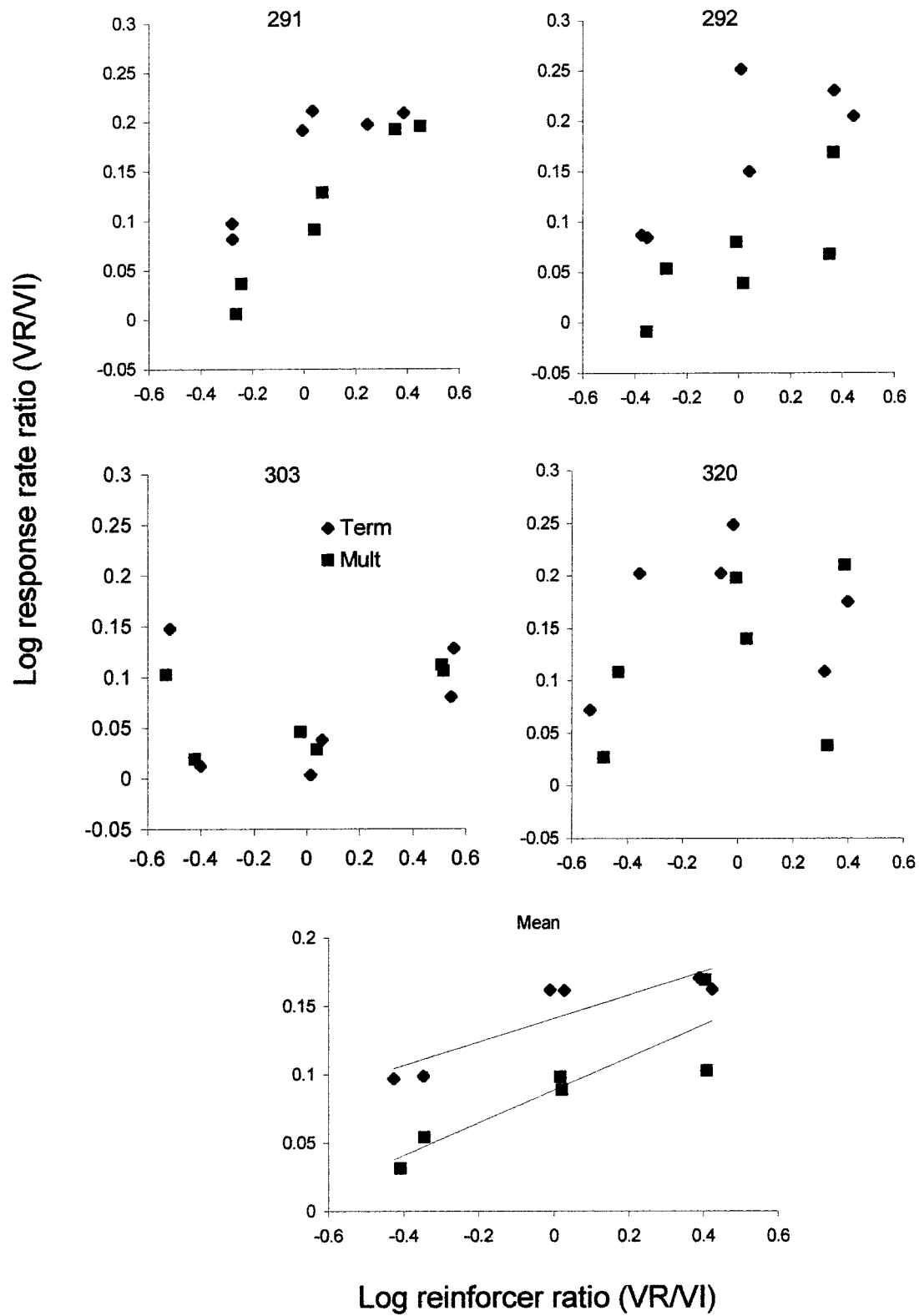
which is a version of the generalized matching law with response and reinforcer rates subscripted L and R to designate left and right components, and with parameters *a* (sensitivity) and *b* (bias) subscripted *m* to designate resistance. As shown in Figures 5, 6, and 7 (which also present the initial-link preference data discussed above), relative resistance to VT, to VT+ext, and to extinction is reasonably well described by Equation 3. The values of a_m and log (b_m) determined by linear regression are given in Table 4, together with the variance accounted for. For VT, the sensitivity of relative resistance ranged from 0.67 to 1.59, with a mean of 0.98, with an average of 80% (range, 63% to 95%) of the variance explained by Equation 3. For VT+ext, sensitivity ranged from 0.90 to 1.94, with a mean of 1.33, with an average of 73% (range, 58% to 90%) of the variance explained by Equation 3. For extinction, sensitivity ranged from 0.20 to 0.45, with a mean of 0.29, with an average of 40% (range, 11% to 74%) of the variance explained by Equation 3. Without exception, sensitivity was greatest in the VT+ext test and least in the extinction test. Also without exception, the sensitivity of relative resistance was less than the sensitivity of preference.

These results are similar in most respects to those reported by Nevin and Grace (2000b) for constant-duration VI VI schedules. Although average obtained reinforcer rates were somewhat higher in the present study, the overall procedure was similar to that of the earlier study, and the resistance-test methods and measures were identical. Nevin and Grace reported that sensitivity ranged from 0.35 to 0.85, with a mean of 0.62, for VT; from 0.59 to 1.90, with a mean of 1.02, for VT+ext; and from 0.07 to 0.52, with a mean of 0.24, for extinction. Although the ranges overlap, relative resistance was generally more sensitive to the reinforcer ratio here than in the earlier study, and the same ordering of average sensitivity across the three resistance tests was also obtained.
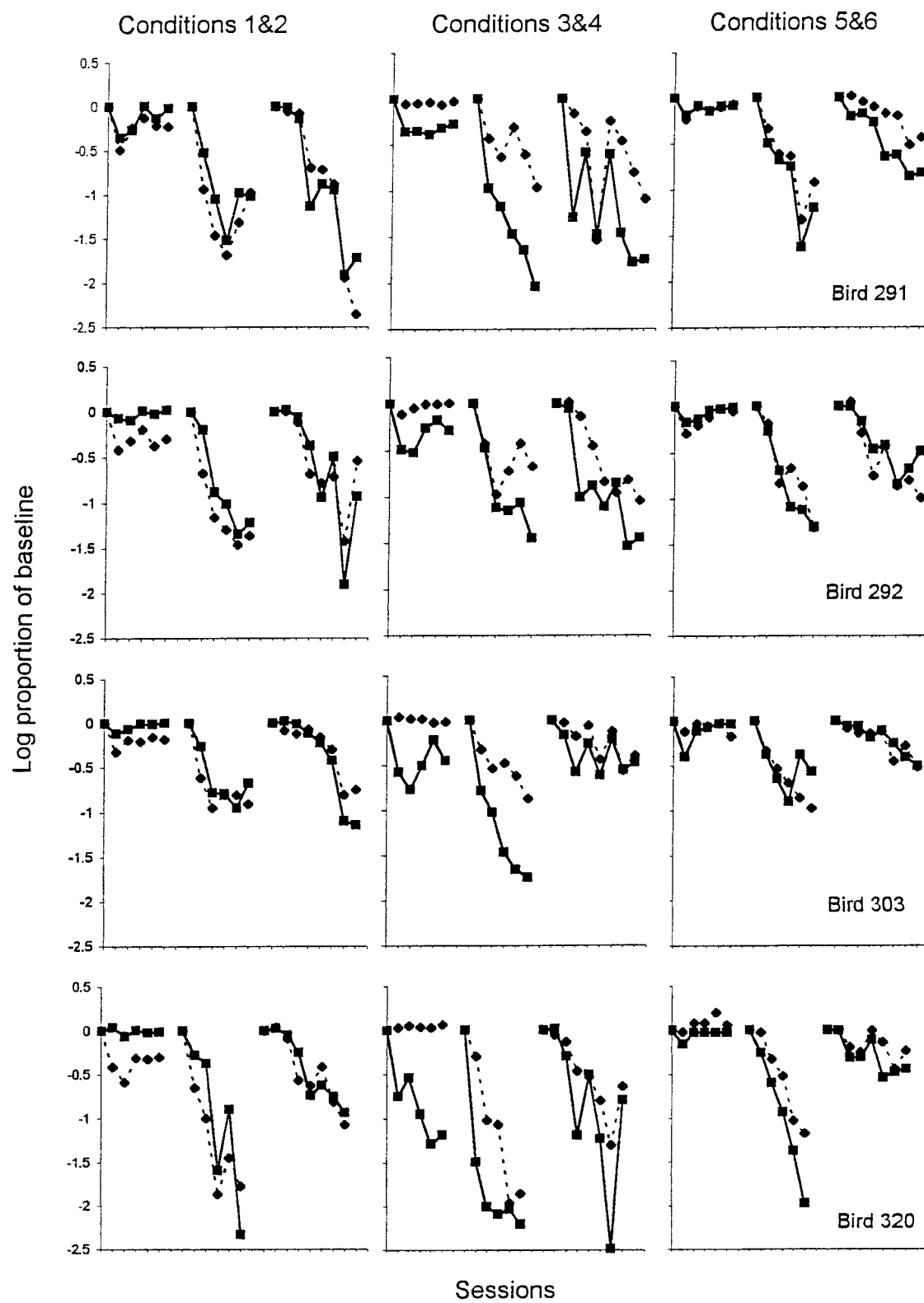
Relative Resistance in VI and VR Schedules

Close inspection of the resistance data in Figures 5, 6, and 7 suggests that the data points for relative resistance were often above the line representing Equation 3 when the VI schedule was in the left component and were below the line when it was in the right component. As for initial-link preference (discussed above), if these deviations are reliably different in direction, they suggest that the VI schedules established greater resistance than the VR schedules independently of the obtained reinforcer ratios. Table 4 presents the difference between the average deviations from the fitted lines between conditions in which the VI multiple-schedule component corresponded to the terminal-link schedule produced by the left or right initial link, showing that the overall difference was positive for all 4 subjects. Pooled across baseline determinations and conditions, these differences were reliably different from zero for Birds 291 (two-tailed *t* test, $p < .001$), 303 ($p < .05$), and 320 ($p < .001$), and for all differences pooled across subjects ($p < .001$). This is evidence of greater resistance for VI over VR schedules when reinforcer rates were taken into account by fits to Equation 3.

We also examined relative resistance in VI and VR schedule components in Conditions 5 and 6, in which reinforcer rates were roughly equated. Rather than comparing resistance differences with fitted estimates, we used actual obtained reinforcer rates in the multiple-schedule components for blocks of five sessions preceding each resistance test. Relative resistance between VI and VR schedules and log ratios of VI to VR reinforcers for the five-session baseline blocks preceding each resistance test were averaged over Conditions 5 and 6 to eliminate key-color bias, and are shown in Figure 12 in the same format as Figure 8. Log obtained reinforcer ratios varied from about −0.08 to 0.04, with the numbers of points evenly divided above and below zero. Thus, our method of equating reinforcer rates was at least reasonably successful in

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Fig. 10. Log response-rate ratio (VR/VI) in terminal links of concurrent chains (term) and in multiple schedules (mult) as functions of the log obtained reinforcer ratios in those terminal links and components for individual birds. Average data are presented in the bottom panel.

Conditions 1&2   Conditions 3&4   Conditions 5&6

Bird 291

Bird 292

Bird 303

Bird 320

Log proportion of baseline

Sessions

the multiple-schedule components as well as the terminal links. Relative resistance was typically greater for the VI over the VR component than would be expected if log obtained reinforcer ratios were the only systematic determiner of resistance to change, as shown by the fact that most of the data fell above the line indicating equality of relative resistance and reinforcement. However, there was a great deal of variability within and between subjects.

It might be argued that VR schedule performance should be more easily disrupted because as response rates decrease, obtained reinforcer rates also decrease, whereas obtained reinforcer rates in the VI component would be essentially constant. A review of our obtained reinforcer-rate data for the VT resistance tests showed that these expectations are correct, and the difference in resistance to VT may depend in part on this difference in obtained reinforcers. However, this argument cannot apply to resistance to VT+ext or to extinction because no reinforcers were presented in either component, and Figure 12 shows that relative resistance was as likely to be greater for the VI schedule in those tests as in the VT tests.

Relations Among Resistance Tests

One purpose of Experiment 2 was to confirm the validity of the difference between log proportions of baseline as a measure of relative resistance when VR and VI schedules are compared. In a similar experiment with VI schedules differing in reinforcer rate, Nevin and Grace (2000b) showed that the difference measure of relative resistance to VT+ext was well predicted by the sum of relative resistance to VT and to extinction. Thus, when differences in log proportion of baseline arise because of variations in reinforcer rate, the difference measure is additive, satisfying a criterion of fundamental measurement (Campbell, 1920). Inspection of Figure 11 shows
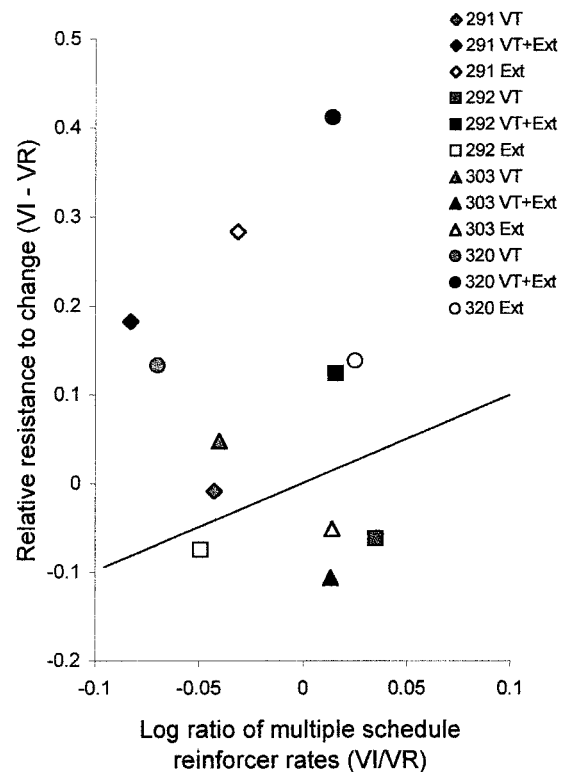
Fig. 12. Resistance to change in the VI component relative to the VR component in each of the three resistance tests is plotted against log obtained baseline reinforcer ratios in those components, pooled for Conditions 5 and 6. The diagonal line indicates equality of these variables. Data points falling above the line indicate that relative resistance in the VI component was greater than expected on the basis of the reinforcer ratio.

that, in the present experiment, response rates were more sharply reduced in the first five sessions of VT+ext tests than in either VT or extinction tests (see Appendix for complete data), which is at least ordinally consistent with additivity. The extent of quantitative consistency is portrayed in Figure 13, which plots relative resistance to VT+ext on the *y* axis as a function of the sum of relative resistance to VT and to extinction on the *x* axis.

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Fig. 11. Multiple-schedule response rates in Experiment 2 during resistance test sessions, expressed as log proportions of baseline response rates in the immediately preceding five sessions. The connected sets of data points represent, from the left, five sessions of VT; five sessions of VT+ext; and the first seven sessions of extinction. The left point in each connected set represents baseline (0). The data for each subject have been averaged for pairs of conditions in which left and right component schedules were reversed with respect to key color. Data for VI components are given by diamonds connected by dashed lines, and data for VR components are given by squares connected by solid lines.
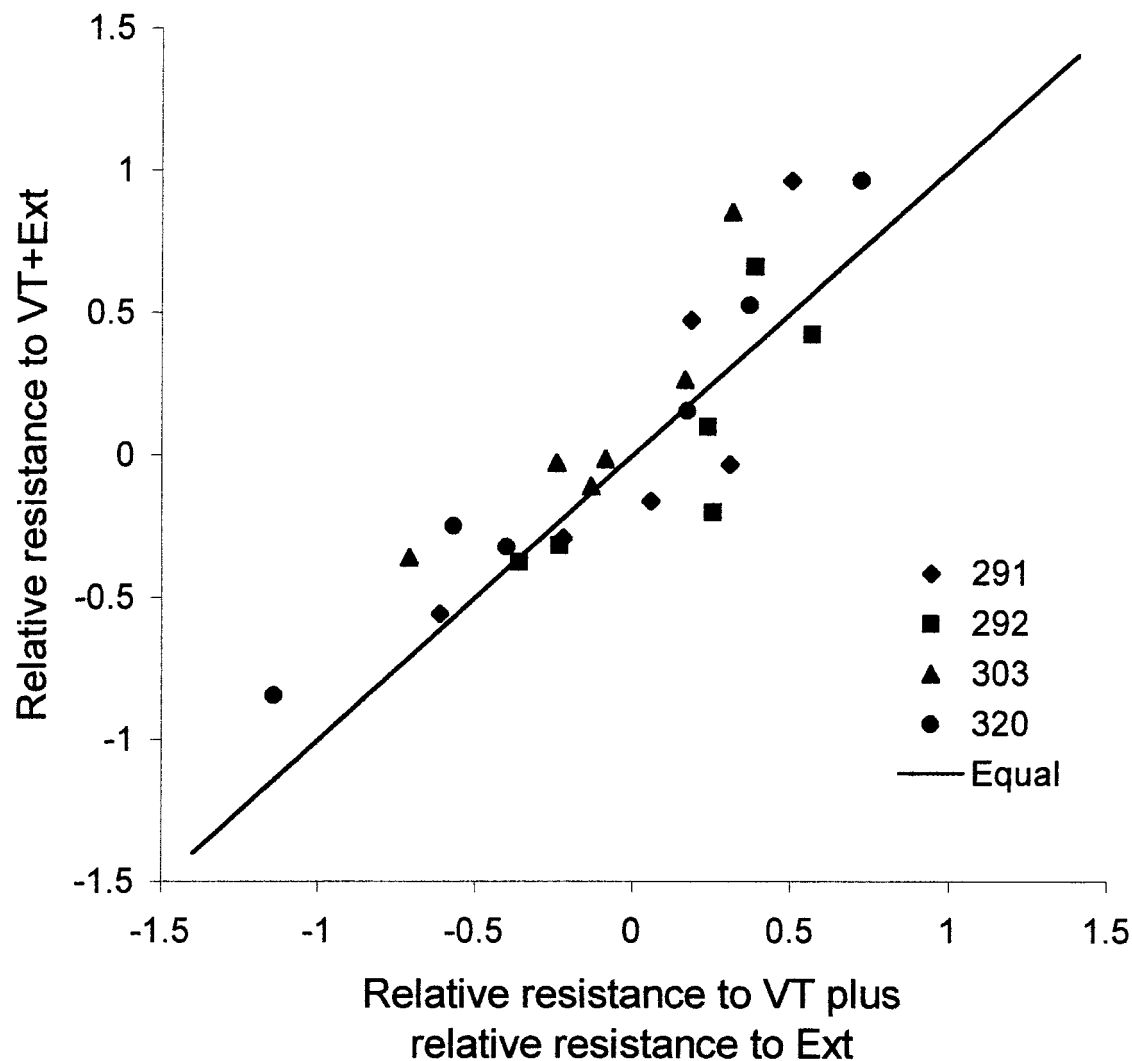
Fig. 13.   Relative resistance to VT+ext is plotted against the sum of relative resistance to VT and to extinction for individual subjects. The line indicates exact agreement.

All data points are based on resistance in the left component relative to the right component. The data points do not deviate consistently from the line indicating exact agreement, and the overall correlation is .87. By comparison, Nevin and Grace (2000b) found an overall correlation of .84. Accordingly, the present data support the earlier conclusion of Nevin and Grace: The between-component difference in log proportions of baseline is a valid measure of relative resistance in that it is additive with respect to testing method within conditions as well as being sensitive to variations in the obtained reinforcer ratio be-

tween conditions. Therefore, the between-component difference should also be a valid measure of differences between VR and VI in resistance to change.

Relations Among Preference, Resistance to Change, and Baseline Response Rates

The individual differences in preference between VI and VR schedules and resistance to change on those schedules (see Figures 8 and 12) may be related to differences in baseline response rates, as was suggested by the resistance data of Experiment 1 (see Figure 3). To explore this possibility, we pooled the

preference data for each of the five-session baselines preceding resistance tests in Conditions 5 and 6, in which reinforcer rates were approximately equal. Likewise, we pooled the data for relative resistance in Conditions 5 and 6 separately for each test. As shown in Figure 14, both preference for the VI alternative and relative resistance in the VI component were positively correlated with the log ratio of VR to VI baseline rates in the terminal links or multiple schedules. Correlation coefficients, pooled across subjects, were .58 ($p < .05$) for preference and .74 ($p < .01$) for relative resistance. Thus, to the extent that a VR schedule established higher response rates than a VI schedule with about the same rate of reinforcement, both preference and relative resistance were greater for VI than for VR.

Relations Between Preference and Relative Resistance

Grace and Nevin (1997) and Nevin and Grace (2000b) examined within-condition correlations between residuals for preference and relative resistance from regression predictions. In both experiments, there was a signficant positive correlation between residuals for preference and relative resistance in VT tests. However, Nevin and Grace failed to find significant correlations for preference and resistance to VT+ext or to extinction alone. In the present experiment, the correlations between residuals for VT were positive for all subjects but failed to reach significance when pooled across subjects ($r = .24$). Correlations between residuals for VT+ext and extinction were .20 and .35, respectively, neither of which is statistically significant. The failure to replicate previous correlations for VT tests may result from the smaller number of conditions in the present experiment.

In Conditions 1 through 4, reinforcer rates differed between the VR and VI components, and the resulting variations in response rates could obscure the effects of other factors that contribute to the residuals for preference and relative resistance with respect to reinforcer ratios. Accordingly, we examined correlations between preference and resistance to change separately in Conditions 5 and 6, in which both measures were correlated with response-rate ratios (Figure 14) and reinforcer rates were approximately equal. After pooling the

data from Conditions 5 and 6 for each resistance test, the difference between relative resistance for the VI and VR components and log multiple-schedule reinforcer ratio for each resistance test (from Figure 12) was correlated with the difference between initial-link preference for the VI terminal link and log terminal-link reinforcer ratio in the immediately preceding five-session block (from Figure 8). The correlation coefficients were .77, .99, and .36 for VT, VT+ext, and extinction, respectively. When the relative resistance and preference data were averaged over the three resistance tests, the rank-order correlation of preference and relative resistance across birds was 1.0, which has a chance probability of $1/24$ with $N = 4$. Thus, preference and relative resistance were significantly correlated across subjects when average reinforcer rates were about equal and individual variations in obtained reinforcer rates were taken into account.

DISCUSSION

Experiment 2 asked whether preference and resistance to change were related to the differences in reinforcement contingencies defined by VR and VI schedules and the resulting differences in the response rates. The results showed that when reinforcer rates were taken into account by generalized-matching-law analyses, VI schedules were preferred to VR schedules and VI schedules established greater relative resistance to change, although the magnitudes of these effects varied considerably across subjects. When reinforcer rates were approximately equal, the magnitudes of these effects were correlated with the extent to which the VR schedules maintained higher response rates than the VI schedules, replicating the major findings of Experiment 1 despite substantial differences in procedure and component reinforcer rates.

GENERAL DISCUSSION

Summary of the Present Results

Experiment 1 asked whether relative resistance to change depended on ratio versus interval schedules of food reinforcement, and Experiment 2 explored the relations among preference, relative resistance, and the ratio of reinforcers arranged by ratio versus inter-

val schedules. Both experiments found that when obtained reinforcer rates were similar, interval-schedule performance was generally more resistant than ratio-schedule performance, and Experiment 2 found that interval schedules were generally preferred to ratio schedules when variations in reinforcer rates were taken into account. When reinforcer rates were similar, individual variations in relative resistance and preference were correlated with the difference between baseline response rates established by ratio versus interval contingencies. In addition, Experiment 2 found that preference and relative resistance depended on the ratio of obtained reinforcer rates in ways that were generally similar to results of previous studies using VI schedules of food reinforcement. Finally, as in our previous studies using the same paradigm (Grace & Nevin, 1997; Nevin & Grace, 2000b), preference was more sensitive to reinforcer ratios than was relative resistance.
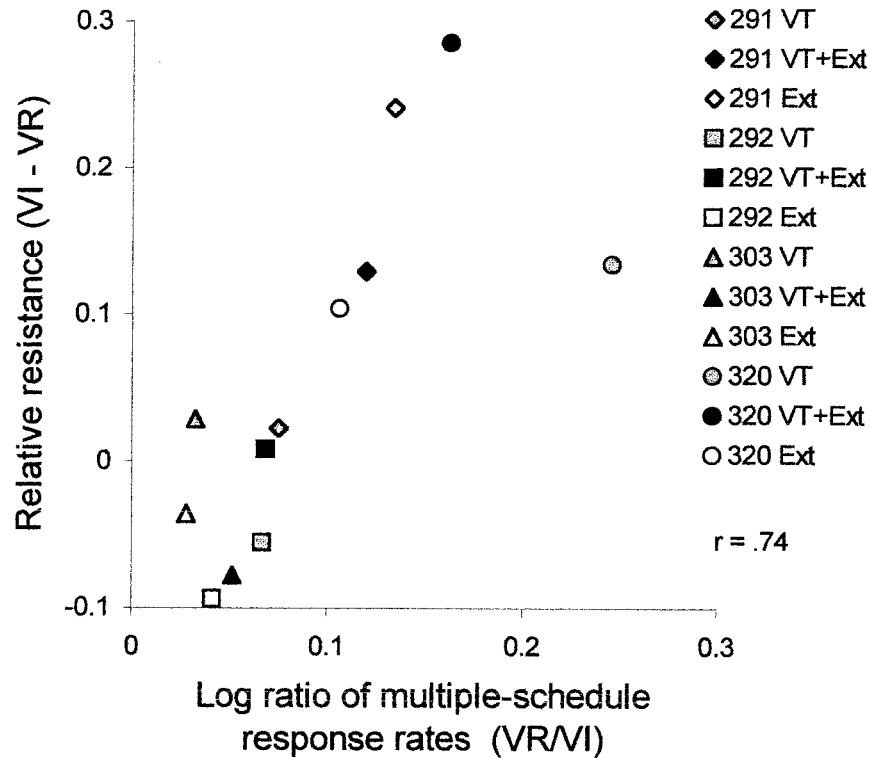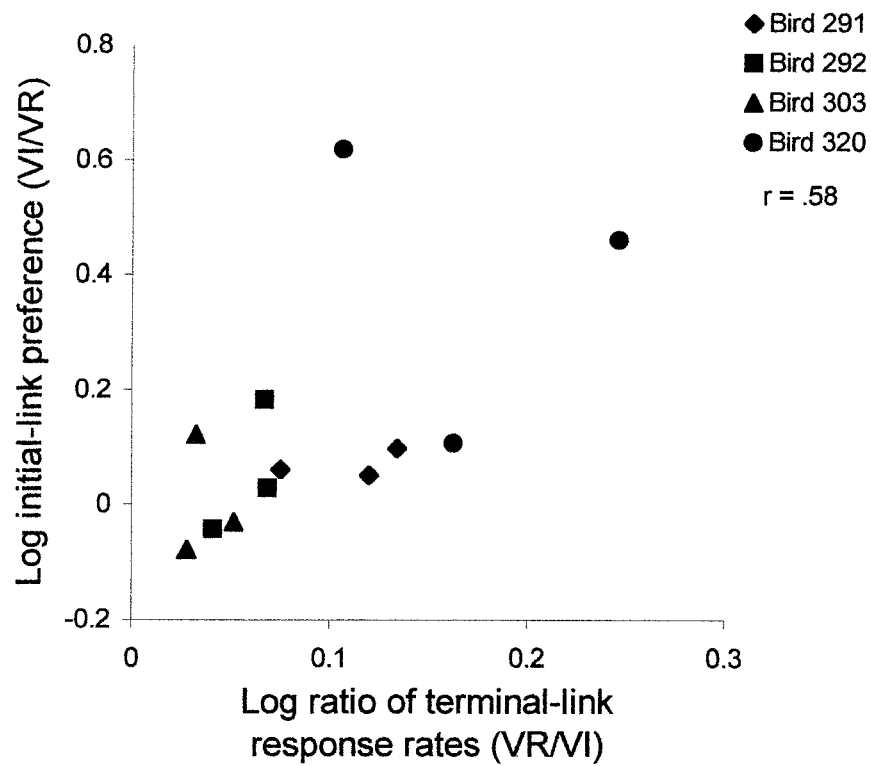
Response Rates and Resistance to Change with Equated Reinforcer Rates

Experiment 1 compared resistance to change in multiple RR and RI schedules, and Conditions 5 and 6 of Experiment 2 compared resistance in multiple VR and VI schedules, in which similar reinforcer rates were arranged by different methods in the two experiments. Both experiments found that during disruption, the degree to which response rates relative to baseline in the interval component were greater than those in the ratio component was correlated with the degree to which the ratio schedules maintained higher baseline response rates than the interval schedules. The average reinforcer rate in the RR and RI components of Experiment 1 was about 100 per hour, and the average reinforcer rate in the VR and VI components of Conditions 5 and 6 of Experiment 2 was about 350 per hour. Perhaps because of this difference in reinforcer rates, average response rates in both components were sub-

stantially higher in Experiment 2 than in Experiment 1, and the ratio of VR to VI response rates in Experiment 2 was substantially less than the ratio of RR to RI response rates in Experiment 1. Also, in Experiment 2, response rates decreased in virtually all resistance tests, whereas in Experiment 1 they often increased, especially in the interval component.

Despite these differences between experiments, relative resistance was similarly correlated with the ratio of the immediately preceding baseline response rates in ratio and interval components in both experiments. The contingencies specified by ratio versus interval schedules and the reinforcer rates were the same for all subjects within each experiment, so the correlations shown in Figures 3 and 14 arose from unsystematic variation in baseline response rates between subjects. The implication is that the effects of ratio versus interval schedules on resistance to change depended on the way in which those contingencies affected the response rates of individual subjects rather than on the schedule contingencies per se.

This conclusion appears to contradict that of Lattal et al. (1998), who observed greater persistence on a progressive-interval schedule than on a progressive-ratio schedule despite similar overall response rates. However, Lattal et al. observed break-and-run performance on the progressive-ratio schedule, with running rates that were generally greater and postreinforcement pauses that were generally longer than on the yoked-interval schedule, in which responding was fairly steady between reinforcers. These differences in patterns of responding complicate the assessment of resistance to change in relation to overall response rate.

Four previous studies have examined resistance to change in multiple schedules with equated reinforcer rates and differing response rates established by various explicit contingencies. A review and reanalysis of

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Fig. 14. The upper panel shows the correlation between log initial-link preference for VI over VR terminal links and log terminal-link response-rate ratios (VR/VI). The lower panel shows the correlation between resistance in VI relative to VR multiple-schedule components and log multiple-schedule baseline response-rate ratios (VR/VI). In the upper panel, data points are based on baseline sessions preceding each resistance test, combined across Conditions 5 and 6. In the lower panel, data points are coded to indicate the type of resistance test, again combined across Conditions 5 and 6.

their data, recalculated exactly as in the present experiments, suggests that the correlations depicted in Figures 3 and 14 have substantial generality.

Blackman (1968, Experiment 2) trained 6 rats on multiple VI VI schedules with tandem pacing requirements that established different response rates with equated reinforcer rates in the components, and found that low-rate responding was more resistant to conditioned suppression than high-rate responding. When shock intensity was 0.5 mA, the difference in log suppression ratios between low-rate and high-rate components (which is exactly analogous to our measure of relative resistance between interval and ratio components) was positively correlated with the log ratio of high to low baseline rates ($r = .27$, $N = 6$, *ns*). (Data were taken from Blackman's Tables 4 and 5. Stronger shocks often reduced responding in the preshock signal to zero, making it impossible to calculate relative resistance.)

Nevin (1974, Experiment 5) trained 4 pigeons on multiple VI 1-min VI 3-min schedules with either high-rate or low-rate contingencies in tandem with each reinforcer rate across two conditions. In each condition, response rates were disrupted by two presentations of intercomponent food at different rates. For 2 birds, responding was relatively more resistant to change in the low-rate component; results were less clear for the other 2 birds. The between-condition correlation of relative resistance (low rate minus high rate) and log baseline ratios (high:low), pooled across subjects and tests, was strongly positive ($r = .85$, $N = 8$, $p < .01$) for VI 1 min, but less so ($r = .40$, $N = 8$, *ns*) for VI 3 min. (Data were taken from Nevin's files; unfortunately, the data for extinction have been lost.)

Fath et al. (1983) repeated Nevin's Experiment 5 with 6 pigeons trained on multiple VI 1-min VI 1-min schedules with tandem pacing requirements that gave high or low response rates in the components. Response rates were disrupted by presenting intercomponent food at six different amounts. Because Fath et al. reported only a single baseline value per component for each bird, we averaged the log relative decrements produced by the six amounts. Averaged across subjects, there was little difference in resistance to change in the high-rate and low-rate components. However, there was a substantial positive correlation across birds between the log ratio of baseline response rates and relative resistance ($r = .62$, $N = 6$, *ns*). (Data were taken from Fath et al., Figure 1, enlarged two times and measured to the nearest 0.5 mm, which was equivalent to 0.015 log unit.)

Lattal (1989) performed a similar experiment with four pigeons in multiple VI VI schedules with tandem differential-reinforcement-of-high-rate or DRL contingencies, and disrupted response rates by three presentations of intercomponent food at different rates. Lattal obtained consistently greater relative resistance in the low-rate component, and again, relative resistance was positively correlated with log baseline ratios when data were pooled across birds and tests ($r = .34$, $N = 12$, *ns*). (Data were taken from Lattal's Table 1.)

It appears that when reinforcer rates are equated in two-component multiple schedules that arrange differential reinforcement with respect to response rate, the lower response rate is generally more resistant to change, and the extent of the difference is positively correlated with the extent to which response rates are differentiated in baseline. Why might this be? One possible account is suggested by behavioral economics, according to which the ratio of responses to reinforcers is construed as unit price (for review, see Hursh, 1984; Hursh & Winger, 1995). Demand curves portraying the relation between consumption and unit price almost universally show that demand becomes more elastic (i.e., less resistant to price changes) as unit price increases. With respect to the present findings, when response rate is greater in one component than in a second component with the same reinforcer rate, unit price is higher in the first component, so perhaps responding is more elastic in the first component as a result. Thus, individual variation in response rates in two schedule components with different contingencies but the same reinforcer rates would lead to greater elasticity in the component with the greater number of responses per reinforcer (for discussion of relations between elasticity of demand and resistance to change, see Nevin, 1995).

This account also predicts that if two VI schedule components with the same reinforcer rates maintain different response rates, re-

sponding should be more resistant to change in the component with the lower response rate. Nevin and Grace (1999) arranged two pairs of multiple VI VI schedules within sessions, with 160 and 40 reinforcers per hour in the rich pair and 40 and 10 reinforcers per hour in the lean pair. Response rates were reliably higher in the 40 per hour component in the lean pair than in the rich pair. Resistance to prefeeding was the same in the two 40 per hour components, and resistance to extinction was greater in the 40 per hour component in the lean pair despite its higher response rate. Nevin (1992a) had previously found greater resistance to both prefeeding and to extinction in a 60 per hour schedule alternated with 10 per hour in one condition than with the same schedule alternated with 300 per hour in a second condition, and response rate in the 60 per hour component was higher in the former condition. Neither of these results is consistent with the behavioral economic account of relative resistance advanced above. Moreover, in experiments comparing resistance to change in components with unsignaled delay as opposed to immediate reinforcement, Bell (1999) and Grace et al. (1998) found that both response rate and resistance were lower in the component with delayed reinforcement despite equated reinforcer rates. Thus, the conditions under which differences in response rate affect resistance to change when stimulus–reinforcer relations are the same in two components remain obscure.

Relations Among Relative Resistance, Preference, and Behavioral Momentum

Experiment 2 confirmed the results of several previous studies showing covariation in preference and relative resistance to change in that both dependent variables were correlated with baseline reinforcer-rate ratios in terminal links and multiple-schedule components. In previous articles, we have argued that preference and relative resistance are independent indicators of a single construct representing the organism's history of reinforcement. In the metaphor of behavioral momentum, that construct is analogous to the mass of a physical object which can be evaluated independently either by gravitational attraction or by resistance to change of velocity, where mass and velocity are them-

selves independent attributes of a moving body (see Nevin & Grace, 2000a, and related commentary). The finding that response rates can affect preference and relative resistance challenges the independence of the behavioral analogues of mass and velocity. It also challenges the assumption that the effects of reinforcement history depend solely on stimulus–reinforcer relations. It does not, however, challenge the proposition that preference and relative resistance provide convergent measurement of the central construct in behavioral momentum theory.

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APPENDIX

For concurrent chains, total initial-link responses, terminal-link response rates, and total terminal-link reinforcers obtained during the five sessions preceding each resistance test on the left and right keys. For corresponding multiple-schedule components, baseline response rates and total reinforcers obtained during the five sessions preceding each resistance test, and average response rates for the first five sessions of each test. Response rates greater than 100 per minute have been rounded to the nearest whole number.

Bird	Before	Concurrent-chain baseline						Multiple-schedule baseline				Resistance tests		
		IL	IR	TL	TR	L rft	R rft	L comp	R comp	L rft	R rft	Test	L comp	R comp
291														
Condition 1	VT	1,268	2,245	58.7	80.9	94	125	72.3	96.1	98	153	VT	51.3	77.6
VI 18 L	VT+ext	1,028	3,186	72.7	115.0	95	179	98.4	156.0	95	255	VT+ext	18.3	42.3
VR 18 R	ext	721	3,577	73.3	126.0	101	206	89.0	152.0	95	242	ext	38.4	50.8
Condition 2	VT+ext	3,469	1,061	127.0	76.3	205	78	162.0	103.0	262	91	VT+ext	10.7	2.3
VR 18 L	VT	3,506	1,286	137.0	85.6	220	105	160.0	103.0	261	89	VT	114.0	49.1
VI 18 R	ext	4,241	1,069	152.0	95.5	253	97	152.0	96.6	240	91	ext	86.2	54.0
Condition 3	VT	1,269	3,029	156.0	132.0	129	235	173.0	168.0	136	229	VT	86.9	144.0
VR 37 L	VT+ext	825	3,915	162.0	117.0	113	227	166.0	147.0	130	232	VT+ext	15.7	50.2
VI 7.5 R	ext	622	3,932	147.0	123.0	123	232	162.0	146.0	125	224	ext	24.5	53.3
Condition 4	VT+ext	3,067	894	129.0	148.0	231	136	159.0	168.0	229	127	VT+ext	39.8	4.6
VI 7.5 L	VT	3,115	811	120.0	143.0	237	108	143.0	152.0	213	127	VT	113.0	66.1
VR 37 R	ext	4,078	600	119.0	153.0	229	123	156.0	144.0	232	114	ext	83.8	44.8
Condition 5	VT	1,528	2,593	145.0	99.0	171	165	164.0	136.0	177	164	VT	66.0	73.2
VR 25 ± L	VT+ext	1,148	3,017	157.0	104.0	154	157	184.0	130.0	199	167	VT+ext	24.5	33.9
VI 10.4 R	ext	1,257	3,004	165.0	97.9	167	177	175.0	123.0	202	159	ext	111.0	97.2
Condition 6	VT	1,849	2,379	116.0	167.0	153	196	145.0	170.0	169	191	VT	99.0	140.0
VI 10.4 L	VT+ext	1,278	2,661	101.0	163.0	157	160	141.0	173.0	160	197	VT+ext	29.7	39.4
VR 25 ± R	ext	1,812	2,761	88.8	167.0	170	161	132.0	172.0	164	153	ext	112.0	60.0
292														
Condition 1	VT	385	3,365	98.2	141.0	91	222	105.0	133.0	96	210	VT	55.8	124.0
VI 18 L	VT+ext	392	3,878	70.6	133.0	92	216	94.8	149.0	101	239	VT+ext	13.7	36.9
VR 18 R	ext	313	3,521	75.6	141.0	101	224	101.0	161.0	93	226	ext	41.1	77.7
Condition 2	VT+ext	3,055	464	144.0	103.0	242	97	131.0	115.0	199	100	VT+ext	24.2	5.8
VR 18 L	VT	2,930	358	144.0	85.1	228	89	143.0	124.0	232	102	VT	138.0	56.8
VI 18 R	ext	3,057	401	146.0	83.0	239	99	152.0	126.0	245	99	ext	112.0	74.3
Condition 3	VT	360	4,640	162.0	146.0	109	242	160.0	144.0	112	225	VT	105.0	143.0
VR 42 L	VT+ext	480	3,125	170.0	132.0	104	234	170.0	150.0	126	229	VT+ext	27.4	55.6
VI 7.35 R	ext	411	3,502	164.0	131.0	100	227	164.0	143.0	123	231	ext	68.0	93.2
Condition 4	VT+ext	3,492	358	106.0	143.0	242	105	139.0	126.0	215	97	VT+ext	40.7	15.3
VI 7.35 L	VT	3,811	287	108.0	118.0	200	78	141.0	142.0	225	105	VT	124.0	50.0
VR 42 R	ext	4,259	319	113.0	138.0	221	97	135.0	138.0	234	96	ext	51.7	29.1
Condition 5	VT	919	2,888	148.0	69.2	154	163	156.0	125.0	149	155	VT	112.0	76.9
VR 25 ± L	VT+ext	978	3,160	161.0	88.5	169	165	159.0	132.0	150	150	VT+ext	60.0	28.9
VI 10.91 R	ext	1,046	2,936	163.0	107.0	178	163	170.0	147.0	147	149	ext	80.4	64.9
Condition 6	VT	1,738	2,363	107.0	136.0	161	174	111.0	121.0	151	134	VT	102.0	123.0
VI 10.91 L	VT+ext	1,220	3,456	106.0	157.0	167	162	137.0	156.0	145	135	VT+ext	36.3	23.1
VR 25 ± R	ext	984	3,364	109.0	161.0	163	202	131.0	137.0	153	198	ext	65.6	98.6
303														
Condition 1	VT	639	6,735	167.0	202.0	93	332	150.0	193.0	99	305	VT	113.0	187.0
VI 18 L	VT+ext	616	7,258	167.0	203.0	93	337	157.0	201.0	93	318	VT+ext	35.8	62.3
VR 18 R	ext	547	7,631	168.0	198.0	98	328	162.0	204.0	96	324	ext	110.0	139.0
Condition 2	VT+ext	8,444	543	221.0	163.0	349	92	205.0	156.0	330	100	VT+ext	43.5	22.8
VR 18 L	VT	8,547	558	220.0	165.0	361	98	209.0	160.0	334	99	VT	187.0	85.2
VI 18 R	ext	7,613	633	219.0	164.0	353	107	190.0	151.0	307	102	ext	165.0	120.0
Condition 3	VT	861	7,200	204.0	196.0	127	296	176.0	184.0	95	290	VT	141.0	173.0
VR 51 L	VT+ext	655	7,725	198.0	192.0	106	288	198.0	172.0	118	287	VT+ext	16.4	73.3
VI 5.86 R	ext	586	8,209	210.0	207.0	114	288	191.0	185.0	115	292	ext	69.6	132.0
Condition 4	VT+ext	6,277	735	205.0	165.0	296	106	188.0	161.0	298	90	VT+ext	49.3	20.7
VI 5.86 L	VT	9,960	546	215.0	131.0	294	72	170.0	139.0	278	76	VT	185.0	22.8
VR 51 R	ext	9,056	631	230.0	167.0	304	94	213.0	151.0	291	89	ext	155.0	103.0

APPENDIX

(*Continued*)

Bird	Before	Concurrent-chain baseline						Multiple-schedule baseline				Resistance tests		
		IL	IR	TL	TR	L rft	R rft	L comp	R comp	L rft	R rft	Test	L comp	R comp
Condition 5	VT	3,462	1,957	228.0	238.0	185	214	198.0	231.0	187	190	VT	173.0	173.0
VI 9.47 L	VT+ext	3,495	2,168	236.0	230.0	187	195	209.0	222.0	186	171	VT+ext	42.7	79.6
VR 24 ± R	ext	4,079	1,601	225.0	226.0	187	168	192.0	212.0	187	169	ext	126.0	174.0
Condition 6	VT	3,077	3,044	226.0	208.0	237	178	207.0	208.0	221	185	VT	172.0	169.0
VR 24 ± L	VT+ext	4,024	2,169	235.0	208.0	204	193	209.0	175.0	191	186	VT+ext	53.4	54.8
VI 9.47 R	ext	4,663	1,277	228.0	216.0	201	191	206.0	200.0	193	185	ext	138.0	142.0
320														
Condition 1	VT	466	4,038	89.1	142.0	89	234	95.0	155.0	101	239	VT	44.8	139.0
VI 18 L	VT+ext	465	4,484	101.0	148.0	98	241	108.0	158.0	101	248	VT+ext	7.8	42.4
VR 18 R	ext	445	4,341	108.0	156.0	103	250	76.9	141.0	91	227	ext	38.4	66.0
Condition 2	VT+ext	2,444	700	81.5	101.0	137	96	81.7	106.0	124	94	VT+ext	17.5	9.8
VR 18 L	VT	4,542	469	134.0	84.6	224	102	132.0	101.0	206	90	VT	140.0	38.4
VI 18 R	ext	4,233	468	148.0	97.5	241	94	160.0	136.0	260	94	ext	132.0	93.5
Condition 3	VT	381	4,732	151.0	92.7	115	230	137.0	114.0	88	246	VT	25.2	122.0
VR 44 L	VT+ext	546	3,467	137.0	71.0	92	231	133.0	91.8	93	238	VT+ext	2.3	22.0
VI 6.92 R	ext	786	2,856	138.0	104.0	104	247	139.0	113.0	86	239	ext	78.0	76.4
Condition 4	VT+ext	3,512	386	85.0	109.0	248	59	111.0	95.5	231	67	VT+ext	11.5	1.9
VI 6.92 L	VT	4,174	470	92.6	124.0	257	78	111.0	124.0	232	78	VT	127.0	20.4
VR 44 R	ext	4,239	358	128.0	128.0	259	86	154.0	134.0	245	87	ext	65.3	43.4
Condition 5	VT	3,117	714	77.4	141.0	160	169	94.2	143.0	149	181	VT	119.0	147.0
VI 10.84 L	VT+ext	2,905	1,809	90.9	139.0	151	125	94.7	138.0	151	154	VT+ext	41.0	40.4
VR 24.2 ± R	ext	3,025	416	94.3	138.0	174	127	117.0	141.0	144	143	ext	83.4	87.0
Condition 6	VT	1,078	2,042	115.0	52.9	173	149	134.0	65.5	172	151	VT	104.0	76.7
VR 24.2 ± L	VT+ext	1,804	1,836	110.0	63.6	156	151	133.0	91.8	139	151	VT+ext	18.2	31.6
VI 10.84 R	ext	982	2,316	95.4	64.4	107	153	115.0	85.0	144	160	ext	73.6	76.0